Imperial College London
Department of Civil and Environmental Engineering

Towards Resolving Data Scarcity in Water Resources Management

William Andrew Veness

Submitted in part fulfilment of the requirements for the degree of Doctor of Philosophy in Civil and Environmental Engineering Research and the Diploma of Imperial College London

February 2024

Abstract

There is global consensus among scientists and policy makers that the scarcity of high-resolution water monitoring data remains one of the most fundamental bottlenecks to sustainable water resources management (WRM). This is especially the case in the Horn of Africa study region, where droughts frequently devastate livelihoods through the collapse of unmonitored water supply infrastructure. However, improving monitoring technologies, telecommunications, and WRM institutional capacities significantly increase the feasibility of collecting hydrological and water security data for integration into decision-making systems. In this study, I use mixed-methods research to assess the potential role of these data and how high-resolution monitoring systems can be upscaled. Through expert interviews, I find that the availability of water monitoring data can support a shift of WRM and drought management away from reactive mechanisms, where the planning of interventions and their financing are principally guided by socio-economic signals of humanitarian needs. Instead, proactive management systems can be developed, where water monitoring evidence guides a more localised planning and financing of actions by providing more confident value propositions for ex-ante investments. Anticipatory actions, taken in the critical window between a drought's first forecast and the onset of humanitarian response, may be rapidly financed through pre-positioned mechanisms if high-resolution water monitoring data is available. To advance the investment basis for hydrological data, I use interview findings to map groundwater data's benefits to 18 stakeholder groups, notably identifying its capability to evolve WRM methods towards evidence-based, decentralised and anticipatory practices. To advance the feasibility of monitoring, I present new quantitative methods for upscaling groundwater monitoring systems and a 5-stage framework of expert recommendations for addressing monitoring implementation barriers. The thesis makes important contributions to the investment and feasibility bases for water monitoring, and I conclude by identifying 27 further research opportunities to build upon its findings.

Acknowledgements

I first wish to extend my gratitude to the individuals, communities, organisations and collaborators in the Horn of Africa who have supported this research. Without their help, much of my work would not have been possible. I sincerely hope that my work returns value to those who have helped me. I owe special mentions to Kenneth Oyik, Khaled Esse Haibe, Faisal Hashi, Flavian Muthusi, Osman Degelleh, Omar Jama, Dr Yazidhi Bamutaze and Douglas Mulangwa, international colleagues Paz Lopez-Rey, John Heelham, Sameer Kariya and Georgie Krause, and to the 42 interviewees who donated their time experience to my study. It was their engagement especially that catalysed my research and personal understanding.

I have been incredibly fortunate to have my two supervisors. Professor Adrian Butler's rare blend of patience and intense enthusiasm was integral in developing my enthusiasm for hydrology. Our periodic meetings were a beacon providing motivation through unusual circumstances in my first 2 years, and I cherish the memories of those Friday afternoons spent largely debugging my code together on screen-share. I remain slightly in awe of my lead supervisor, Professor Wouter Buytaert. He has an ability to process my lengthy melanges of updates, ideas and questions before responding immediately with clear, concise logic. I don't believe I arrived to the PhD with many of the skills he has, but he has patiently developed them in me too. Thank you, Wouter, for the opportunity to learn from you.

My gratitude extends to UKRI, NERC's SSCP DTP, the FCDO, the Building Resilient Communities in Somalia Consortium and Concern Worldwide for backing my project, as well as collaborating organisations UN FAO SWALIM and Somaliland's Ministry of Water Resources Development. I am also grateful to the Grantham Institute, whose network adds huge value to the PhD experience, helping me secure an internship with the UK Government Office for Science during my studies. I thank Dr Claire Meara for taking me under her wing during those 3-months – I developed many skills and a great deal of confidence during our short time together.

I have continually encountered new friends who have kept the PhD feeling fresh and exciting throughout. Special mentions to Anna T, Clara GJ, Charles Z, Boris OT, Greta A, Jonny P, Simon M, Simon DS, Neeraj S, Anthony R, Jordi B, Josh K, Brad J, Joe P, Alex B, Emma B, Tom R, Tom B, Jose C, Tom G, Ben H and Maria G. In individual and substantial ways, you have each kept me smiling, curious and feeling supported when I have needed it. Thanks to all of you, and to close friends beyond Imperial who have supported me, notably George F, George W, Megan C, Jordan Y, Katherine T, Jordan S, Dom M, Nikita M, Emma W, Hettie G, Esme S, Coral B, Mira B, Gabriel WH, Sophie M, Miles C, Mo S, Jack D, James B, et al.

My mother, Penny Veness, always wanted one of her children to be a doctor. I don't think this is the type of doctor she had in mind, but her and my father, Andrew Veness, have always supported me whatever I have chosen. This is incredibly enabling, as was the environment they created for me to learn, play and pursue my interests throughout my early life. I have been very lucky for that. To Alex, thank you for embodying the supporting older brother cliché and letting me live life in your slipstream. To my sister, Mimi, I am proud of the closeness we now share, and it is pretty cool that our interests seem to be converging. The love and support from you all, and my grandparents Peter and Hilda Veness, plays a major role in anything I achieve in life, so I hope that you can all take personal pride in this achievement too.

Declaration of Originality

The work presented in this thesis is my own, except where otherwise explicitly indicated.

Copyright Declaration

The copyright of this thesis rests with the author. Unless otherwise indicated, its contents are licensed under a Creative Commons Attribution Non-Commercial 4.0 International Licence (CC BY-NC).

Under this licence, you may copy and redistribute the material in any medium or format. You may also create and distribute modified versions of the work. This is on the condition that: you credit the author and do not use it, or any derivative works, for a commercial purpose.

When reusing or sharing this work, ensure you make the licence terms clear to others by naming the licence and linking to the licence text. Where a work has been adapted, you should indicate that the work has been changed and describe those changes.

Please seek permission from the copyright holder for uses of this work that are not included in this licence or permitted under UK Copyright Law.

Contents

1 Introduction……..13

1.1 Scientific Rationale 13

1.2 Study Region 18

1.3 Aims and Research Objectives 22

1.4 Thesis Structure 22

1.4.1 Chapter 2: Methods 23

1.4.2 Chapter 3: Proactive Drought Management Needs Water Security Data 23

1.4.3 Chapter 4: Updating the Drought Management Framework 23

1.4.4 Chapter 5: Localizing Hydrological Drought Early Warning Using In Situ Groundwater Sensors 24

1.4.5 Chapter 6: Unlocking the Benefits of Groundwater Data 24

1.4.6 Chapter 7: Discussion 25

1.4.7 Chapter 8: Conclusions and Outlook 25

2 Methods……27

2.1 Overview 27

2.2 Research Sequencing 27

2.3 Semi-Structured Interviews 29

2.3.1 Interview Design 29

2.3.2 Ethical Procedures 30

2.3.3 Interview Sampling 31

2.3.3.1 NGO & UN 32

2.3.3.2 Water Authorities and Government 33

2.3.3.3 Academia and Private Consultants 34

2.3.4 Qualitative Analysis 34

2.3.5 Interview Data Presentation 35

2.4 Groundwater Monitoring 35

2.5 Narrative Literature Review: Chapter 4 36

2.6 Analysis and Discussion 36

3 Proactive Drought Management Needs Water Security Data ……38

3.1 Abstract 38

3.2 Introduction 39

3.2.1 Droughts, Early Warning and Early Action 39
3.2.2 Horn of Africa 2021 – 2023: The Genesis of a Drought Crisis 40
3.2.3 Droughts and Food Insecurity 42
3.2.4 Droughts and Water Insecurity 42
3.2.5 Study Rationale 43
3.3 Results 44
3.3.1 Drought Management Barriers 44
3.3.1.1 Information Systems 45
3.3.1.2 Financing 48
3.3.1.3 Capacity 51
3.3.1.4 Physical 52
3.3.1.5 Humanitarian Access 52
3.3.1.6 Political 53
3.3.2 Existing Information Systems 54
3.3.3 Water Security Information Needs 56
3.3.3.1 Water Resource Managers (WRMs) 56
3.3.3.2 Financial Decision Makers 58
3.3.3.2.1 Traditional financing 59
3.3.3.2.2 Index-based Financing 62
3.4 Discussion 63
3.4.1 The Role of Water Security Data for Anticipatory Action 63
3.4.2 Shifting Towards Index-Based Mechanisms of Drought Finance 64
3.4.3 Implementing Water Security Monitoring 67
3.4.4 Research Needs 68
3.5 Conclusions 69
3.6 Supporting Information 72
3.6.1 FSNAU Indicators and Alarm Thresholds 72
3.6.2 List of Figure 3.4 Acronyms 72

4 Updating the Drought Management Framework……..74

4.1 Abstract 74
4.2 Introduction 75
4.3 Defining Drought for DRM Frameworks 78
4.3.1 Paradigm Definitions of Drought 78
4.3.2 The Challenges of Representing Drought Propagation Phases 81
4.3.3 Suitable Drought Definitions for DRM Frameworks 83

4.4 Disaster Risk Management Terminology and Drought 85
4.5 Updating the Common Drought Management Framework 89
4.5.1 Defining a Place for Anticipatory Action 89
4.5.2 Shifting Towards Resilience Building 93
4.6 Actioning the Framework 95
4.7 Conclusions 97

5 Localizing Hydrological Drought Early Warning Using In Situ Groundwater Sensors……..……98

5.1 Abstract 99
5.2 Introduction 100
5.2.1 Current Drought Monitoring Methods for Early Warning 100
5.2.2 Modern Sensors for In-Situ Groundwater Monitoring 102
5.3 Methods 104
5.3.1 Modelling approach 104
5.3.2 Input Data 104
5.3.3 Groundwater Model 105
5.3.4 Calibration Method 107
5.3.5 Calibration Length Analysis 108
5.3.6 Model Simulations during 2016/17 & 2019 Droughts 109
5.4 Results & Discussion 110
5.4.1 Calibration Length Analysis 110
5.4.2 Model Performance 111
5.4.3 Simulating the 2017 & 2019 Droughts 112
5.4.4 Discussion: Model applications for DEWSs 114
5.5 Conclusions 115
5.6 Data Availability Statement 116
5.7 Supporting Information 116
5.7.1 AquiMod Recharge Model 117
5.7.2 Modified AquiMod Groundwater Model 117
5.7.3 Parameter Sensitivity During 7-week Calibration Procedure 119
5.7.4 Literature-derived Parameters for Uncalibrated AquiMod Model 120
5.7.5 Example Radial Flow Abstraction Model for Coupling to AquiMod 120

6 Unlocking the Benefits of Groundwater Data……..……122

6.1 Abstract ... 122
6.2 Introduction ... 123
6.3 Results and Discussion ... 125
6.3.1 Mapping the Benefits of Groundwater Monitoring Data ... 125
6.3.1.1 Benefits for Water Resource Managers (WRMs) ... 125
6.3.1.2 System-wide Benefits for WRMs ... 131
6.3.1.3 Benefits for Emerging Stakeholders ... 132
6.3.2 Discussion: Systemic Decentralisation of WRM ... 137
6.3.3 Implementation Challenges ... 138
6.3.4 Groundwater Monitoring Implementation Framework ... 141
6.3.4.1 Stage 1 – Preparation & Procurement ... 141
6.3.4.2 Stage 2 – Pilot ... 143
6.3.4.3 Stage 3 – Expansion ... 145
6.3.4.4 Stage 4 – Institutionalisation ... 145
6.4 Conclusions ... 149
6.5 Supporting Information ... 152
6.5.1 Recommended Groundwater Data Presentation ... 152

7 Discussion……...……...155

7.1 Overview ... 155
7.2 Towards Resolving Data Scarcity in WRM ... 155
7.3 Limitations, Confidence and Generalisability of Findings ... 156
7.3.1 Qualitative Methods ... 156
7.3.2 Quantitative Methods ... 158
7.3.3 Generalisability ... 159
7.4 Attracting Water Monitoring Investments ... 160

8 Conclusions and Outlook……..……162

8.1 Academic Contributions ... 162
8.1.1 Chapter 3 – Proactive Drought Management Needs Water Security Data ... 162
8.1.2 Chapter 4 – Updating the Drought Management Framework ... 163
8.1.3 Chapter 5 – Localizing Hydrological Drought Early Warning Using In Situ Groundwater Sensors ... 164
8.1.4 Chapter 6 – Unlocking the Benefits of Groundwater Data ... 165

8.2 Contribution Towards Resolving Data Scarcity in WRM 166
8.3 Research Outlook 167
9 Bibliography 171

List of Figures

Figure 1.1. Outline of the thesis chapters' content, relevant research objectives and rationale…….26

Figure 2.1. Professional roles of the 42 study participants. The profession reference codes used to anonymise interviewees in the analysis of Chapters 3, 4 and 6 are shown for each role.……...32

Figure 3.1. (a) Cascading impacts of drought in Somalia from 2020 – 2023. Indicators from the UN Food Security Nutrition and Analysis Unit's (FSNAU) early warning dashboard for Baidoa District are plotted (FSNAU, 2023a). The colour of each line shows the 'normal', 'alert' or 'alarm' status of that indicator on the dashboard during that month (status criteria are explained in Supporting Information; Chapter 3.6.1). A timeline of key events in Baidoa and Somalia is documented from grey literature (FEWS NET, 2020; OCHA, 2021a; OCHA, 2023a; OCHA, 2023b; UNHCR, 2021; UNHCR, 2022; IPC, 2022; UN, 2023; WHO, 2023b). NDVI = Normalised Different Vegetation Index. (b) The number of food security indicators above FSNAU's 'alarm' threshold across Somalia's 74 administrative districts (FSNAU, 2023b)…….41

Figure 3.2. The four domains of water security (from Young, 2021). The graphical representation is adapted from a food security review by Jones et al. (2013)……43

Figure 3.3. Barriers to managing drought impacts perceived by experts during the Horn of Africa 2021 – 2023 drought. Themes and sub-themes are shown, scaled to the number of respondents coded to that category…….45

Figure 3.4. (a) Information sources and (b) indicators used by expert respondents to monitor drought. These are thematically categorised as sources of information on physical drought, socio-economic drought, or both. The number of participants using each source or indicator is shown for those that are raised by multiple people. A list of acronyms is provided in Supporting Information 3.7.2…….54

Figure 3.5. An interpretive conceptual framework for water security-centred decision-making, where information needs are met for the rapid approval of proactive, evidence-based actions focussed on water security. Water Resource Managers (WRMs) are the primary users of water security data for planning direct actions that manage water supply systems. Financial decision makers from traditional sources require evidence to justify financing decisions on a cost-benefit basis, and they have a decision-making frame that considers broader development and humanitarian objectives as well as alternative project proposals. Index-based finance sources trigger financial pay-outs once selected indices exceed pre-determined thresholds. The actions and information needs shown are all codes recorded during thematic analysis……64

Figure 3.6. Conceptual model of financing needs satisfaction, comparing drought financing indexed by local water security data with traditional financing methods guided by existing EWSs……...65

Figure 3.7. The table (from FSNAU, 2023b) summarises the indicators displayed on the Food Security Nutrition and Analysis Unit's Early Warning-Early Action (EW-EA) Dashboard and the threshold criteria for those indicators to be categorised as being in 'normal', 'alert' or 'alarm' phases……..72

Figure 4.1. The paradigm disaster management cycle used in DRM including the 6-stages posited by the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015; UNDRR, 2016)……...76

Figure 4.2. The representation of drought propagation by Van Loon (2015), reproduced here, is the paradigm representation of drought categories commonly used in academia, policy and practice (Van Loon, 2015; Peters, 2003; Stahl, 2001; Van Loon, 2013; Ikeda, 2021; IPCC, 2022)……80

Figure 4.3. (a) Observation borehole water level measured twice daily in Hargeisa, Somaliland. (b) Abstraction borehole water level measured twice daily under similar climatic conditions in Borama, Somaliland. The Gu and Deyr rainy seasons are highlighted blue….83

Figure 4.4. Common disaster risk management (DRM) terminologies, with their temporal usage in practice for drought mapped to a paradigm drought propagation timeline. The grey area between mitigation & preparedness and response in the DRM cycle represents a management window between meteorological drought forecasts and response-inducing socio-economic drought, where both terms apply poorly to the unique forecast-based actions taken (Coughlan de Perez et al., 2015; Staupe-Delgado and Kruke, 2018)……..89

Figure 4.5. An updated conceptual framework for drought management, formalising the convergence of traditional DRM concepts with the pragmatic conceptual innovations of anticipatory action and resilience building……..92

Figure 5.1. Location of the three shallow, large diameter wells in Maroodi Jeex, Somaliland……..105

Figure 5.2. Modified AquiMod lumped catchment regional model for a single unconfined aquifer layer……106

Figure 5.3. RMSE for the full calibration and validation period, with calibration lengths varied at weekly intervals……...110

Figure 5.4. (a) Normalized satellite-based proxy indicators of physical drought intensity compared to Well 2's observed daily maximum water levels. Calibrations of (b) Well 1, (c) Well 2 and (d) Well 3 are shown to compare performance with the proxy indicators and an uncalibrated AquiMod groundwater model. Observed water levels and the corresponding calibration targets set at the daily maxima are shown for comparison of fit……..111

Figure 5.5. 2015-20 simulations of the three wells using the 7-week calibration parameters. Water levels are normalized to the distance between the top of the well and the pump inlet depth. The two droughts are indicated from the dates that humanitarian crises were declared by the Somalia president (2017; Guled, 2017) and Oxfam (2019; Barter, 2019). The critical level is the level below which the mean observed dry-season abstraction drawdown would not be possible due to water level falling below the pump inlet……113

Figure 5.6. Dotty plots showing RMSE scores for parameter input values during (a) a 7-week calibration and (b) a 30-week calibration at Well 2……..119

Figure 6.1. Thematic summary of the benefits of groundwater monitoring data for different stakeholders. Stakeholders are grouped as either Water Resource Managers (WRMs), the primary users of groundwater data, or emergent stakeholders – those with no prior experience of groundwater data who can benefit from analysed data. Background descriptions of these stakeholder groups are given in the methods (Chapter 2.3.3). Themes of benefits (bold) and sub-themes from thematic analysis are plotted for each of the 18 different stakeholder categories (underlined)……..136

Figure 6.2. An interpretive conceptual model of the data-enabled transition from centralised WRM paradigms to decentralised WRM……..138

Figure 6.3. Thematic summary of expert-identified challenges for the setup of integrated groundwater monitoring systems……139

Figure 6.4. Expert-guided implementation framework for setting up integrated groundwater monitoring and decision-making systems in resource-scarce contexts. The bullet points represent individual recommendation codes from the thematic analysis of responses to interview Questions 10 – 12 (Chapter 2), whilst the codes are interpretively organised into an approximately chronological 5-stage sequence. Whilst these are pragmatically presented as a sequence, some stage transitions may be concurrent, iterative or cyclical in practice……149

Figure 6.5. Expert recommendations for groundwater data presentation, thematically coded to the relevant stakeholder group……152

List of Tables

Table 4.1. Stages of the Sendai Framework for DRR (UNDRR, 2016), mapped to the actions taken during droughts that can be described by their definition. The drought management actions are collated from interviewees' coded responses to Questions 4 – 7, where they discussed actions taken to manage droughts……86

Table 5.1. Parameter input ranges, calibrated parameter values and RMSE scores for the top scoring 7-week calibration sets at Wells 1, 2 and 3……108

Table 5.2. Parameter values used in uncalibrated AquiMod model simulations……120

Table 8.1. Academic research needs identified during the research study and their importance to policy and practice relevant to resolving data scarcity in Water Resources Management (WRM)……...167

1 Introduction

1.1 Scientific Rationale

A deepening global water crisis threatens international capabilities to sustain 21st Century development pathways and meet basic human rights. Over 750 million people currently do not have access to safe drinking water (Damania, 2019; Naddaf, 2023; WHO/UNICEF, 2021), and increasing anthropogenic and environmental pressures further threaten the sustainability of water supply systems. Population growth, urbanisation, industrialisation and commercial agriculture are intensifying international water demand, whilst climate change, aquifer over-abstraction and land-use change are reducing the reliability of water supply (IPCC, 2022; Scanlon et al., 2023). Hydrometeorological hazard risk is also increasing, disproportionately impacting low- and middle-income countries whose populations account for 91% of global climatic hazard fatalities (Kreibich et al., 2022; WMO, 2021).

The impacts of the water crisis are especially acute in Sub-Saharan Africa, where the rising number of people without basic drinking water services now exceeds 350 million (Naddaf, 2023, WHO/UNICEF, 2021). Droughts overcome water supply infrastructure with a regularity and pervasiveness that stunts long-term development in many of its dryland regions (Carter et al., 2007; Enfors and Gordon, 2008; Noritomo and Takahashi, 2020). For instance, droughts in Somalia during 2011, 2017, 2021 and 2022 have cumulatively caused over 300,000 excess deaths, with the most recent event displacing more than 1 million people and causing 23% of its population to experience daily acute water insecurity (Hillbruner and Moloney, 2012; WHO, 2023b; Warsame et al., 2023). Droughts are most simply defined as a water deficit relative to normal conditions (Van Loon, 2015). The hazard initiates as a rainfall deficit that gradually creates deficits in soil moisture and other hydrological stores (Van Loon, 2015; Lloyd-Hughes, 2014). During droughts, water shortages cause cascading secondary impacts that generate water insecurity, food insecurity and adverse effects that reach all sectors of development (AghaKouchak et al., 2015; Nicholson, 2014; UN-Water, 2021a).

Maintaining water security is a primary objective of water resources management (WRM). It is commonly defined as a stability in water availability, access and use for human consumption (Cook and Bakker, 2012; Young, 2021), though its application has expanded over time to encompass issues of ecology, politics and water-related natural hazards (Jepson et al., 2017; Ringler et al., 2018; Slaymaker et al., 2020). The objectives of its management conceptually overlap with Sustainable Development Goal 6 (SDG 6): ensuring availability and sustainable management of water and sanitation for all (UN DESA, 2022; UN-Water, 2021b). WRM aims to achieve population water security through the sustainable planning, development and management of the coupled human-water system (Loucks et al., 2000; Weiskel et al., 2007). Whilst WRM systems maintain near-complete water security for populations in high-income countries, this goal is rarely met in low- or middle-income countries (Naddaf, 2023). In instances of water insecurity in these countries, water scarcity is rarely the sole cause (Ford et al., 2022; Cosgrove and Loucks, 2015). Instead, water insecurity principally stems from fragile water supply infrastructure, governed by stakeholders with low financial and technical WRM capacities (Ovink et al., 2023; UNESCO, 2022).

Numerous factors constrain the management capacities of WRM stakeholders in low- and middle-income countries (Simukonda et al., 2018). Whilst academic research has not holistically assessed causal chains or root causes, the immediate factors constraining WRM capacities are well-understood (Brown and Farrelly, 2009; Brown et al., 2015; Cosgrove and Loucks, 2015; Weiskel et al., 2007). The factors are considered to fall into 4 major themes, i.e., finance, skills, governance and data (UN-Water, 2022; Vogl et al., 2017).

The underfinancing of WRM and WASH (Water, Sanitation and Hygiene) causes a shortage of staff, equipment and capital for management projects (Ovink et al., 2023; UNESCO, 2022). Just 5% of humanitarian financing in Somalia is allocated to the WASH sector, compared to 43% for food security (Mourad, 2023; Ikeda, 2021; OCHA, 2023a). The funding of WRM in low- and middle-income countries instead depends heavily on annual allocations from national budgets (Alaerts, 2019), which do not meet the growing funding requirements for sustainable management (Machete and Marques, 2021). Skills capacity shortages are another constraint on WRM capabilities to plan, develop and manage water supply networks (Margerum and Robinson, 2015; UN-Water, 2022). Skills capacity-building has previously been overlooked, but it is now the focus of an increasing number of projects such as the United Nations' (UN) capacity development network (Cap-Net, 2023; Margerum and Robinson, 2015; UNESCO,

2022). Political governance, depending on locational context, can also constrain institutional capacities to manage water resources (Buytaert et al., 2016; Cosgrove and Loucks, 2015; Perreault, 2014). For example, many acutely water insecure areas are difficult to access for professional water resource managers (WRMs) due to active conflicts or poor transport infrastructure (Gleick, 2014; Naiga et al., 2015). Furthermore, weak legislation and enforcement of water regulations in many low- and middle-income countries enables large informal water sectors beyond the government's control (Klassert et al., 2023). Political biases are also common, which can reduce government support for WRM capacity in some districts by channelling resources to districts of greater political affinity (Rinaudo, 2002). Political governance barriers to WRM are variable according to local contexts, and global best practices for different WRM governance approaches an active research debate (Buytaert et al., 2016; Cosgrove and Loucks, 2015; Hashi et al., 2016; Klassert et al., 2023; Tantoh et al., 2021; Saravanan et al., 2009).

The fourth factor, monitoring data scarcity, is considered a 'neglected area' in achieving SDG 6 (UN-Water, 2021b), known to restrict WRM capacities but to a relatively unknown extent (Garrick et al., 2017; Gaye and Tindimugaya, 2018; UN-Water, 2021a; UN-Water, 2022). The term 'data', in the context of WRM, encompasses hydrological measurements, either in-situ or satellite-based, and any quantitative or qualitative socio-economic measures relevant to water security such as water prices, household surveys or qualitative reports (Zins, 2007). International forums echo a management cliché, "you cannot manage what you do not measure," in requests for greater investment into water data (UN-Water, 2021a; UNESCO, 2022). In support of these narratives, some studies have deductively assessed the value of individual water monitoring variables for ecosystem or water management, commonly concluding that monitoring has positive valuations and returns on investment (ROIs) when implementations meet user information needs (Hunger and Doll, 2008; Maxwell et al., 2021; Parajka and Bloschl, 2008; UN-Water, 2021a; Zulkafli et al., 2017). However, there has been no systems-level, inductive academic research into the consequences of data scarcity, or, inversely, the potential value of access to full networks of these data for WRM stakeholders in low- and middle-income countries (Hamel et al., 2020; Stewart, 2015; Sugg, 2021). Valuation is fundamental to investment, yet the value of local water monitoring data has not been sufficiently elucidated for potential investors (Garrick et al., 2017; Pandeya et al., 2016; UN-Water, 2021a).

There are further, complex causal factors responsible for local water monitoring data scarcity (Addor et al., 2020; Hamel et al., 2020). Economic costs, the challenges of community engagement and the reliability of monitoring technologies are separately identified as barriers to data collection, but the barriers and their respective causes also have not been holistically assessed for water monitoring systems (Addor et al., 2020; Buytaert et al., 2014; Paul et al., 2018; Vogl et al., 2017). The lack of a granular understanding of the causal factors responsible for hydrological data scarcity has prohibited the design of sustainable solutions and disincentivised investments into upscaling water monitoring in low- and middle-income countries (Adelana, 2009; Foster et al., 2012; IGRAC, 2020; Pavelic et al., 2012; Sarni et al., 2018; UN-Water, 2021b).

Advances in monitoring technologies have substantially reduced the costs and complexities of collecting water monitoring data at greater scale (Buytaert et al., 2014; Calderwood et al., 2020; Paul et al., 2018). Low-cost wireless sensor networks and the Internet of Things (IoT) now automate the collection and transmission of local hydrological data over increasingly pervasive global telecommunication networks (Chan et al., 2020; Calderwood et al., 2020; Kombo et al., 2019; MacAllister et al., 2020). Furthermore, the automated processing, analysis and communication of data on dedicated platforms through artificial intelligence (AI) reduces the technical and staffing capacity hurdles of making these data usable (Sarni et al., 2018; Vitolo et al., 2015). The World Economic Forum describe IoT, AI and emerging sensor technologies as a '4th Industrial Revolution for Water', with numerous opportunities for WRM (Schwab, 2017; Sarni et al., 2018). Technologies are, however, only useful if they meet user information needs and if the institutional capacity is in place to support them (Maxwell et al., 2021; UN-Water, 2021b).

The improving financial, staffing and technical capacities of WRM institutions mean they are increasingly capable of hosting and integrating monitoring systems (Gaye and Tindimugaya, 2018; UN-Water, 2022). Furthermore, a greater uptake of user-centred design and citizen-science approaches increases the viability of collecting long-term local data ethically and sustainably (Maxwell et al., 2021; Nath and Kirschke, 2023; Zulkafli et al., 2017). There is now greater consideration of the potential negative externalities of sensitive data collection and the need to consult local stakeholders in monitoring system design (Buytaert et al., 2014; Hartter et al., 2013). High resolution hydrological data, consumer data, and digital data have a high risk of privacy violation (Zipper et al., 2019), as they risk revealing individuals' personal

details or unequal access valuable water resources (Zipper et al., 2019). Local stakeholder consultations help to ensure that community risks are mitigated, local benefits of monitoring are understood, data sharing permissions are established, and a shared responsibility for monitoring projects is agreed (Dickert and Sugarman, 2005; Helveston, 2015). As higher resolution monitoring networks expand, international protocols for ethical monitoring such as the 'Open Hydrology Principles' are being developed to guide institutional practices. It is now common for academic and implementing institutions to conduct internal ethical review procedures case-by-case for monitoring projects to identify and avert risks (Rangecroft et al., 2021; Zipper et al., 2019).

Conceptual innovations in WRM are also increasing interest in water monitoring (Meadowcroft and Fiorino, 2017; Simion and Kelp, 2019; Schoeman et al., 2016). The use of political ecology, acknowledging the inter-connected nature of the coupled human-water system, is drawing attention to water's value in other sectors of development and the need to monitor its interactions (UNESCO, 2021; Pandeya et al., 2016; Garrick et al., 2017; Swyngedouw, 2009; Wutich and Brewis, 2014). Conceptual innovations in the Disaster Risk Management (DRM) field for droughts and floods are using water monitoring data in their implementation (Guimarães Nobre et al., 2019; Staupe-Delgado and Kruke, 2017). For example, the concepts of resilience building, early action, anticipatory action, early warning systems and forecast-based financing all use water monitoring data to index the financing of actions taken ex-ante, before hazard impacts fully develop (Coughlan de Perez et al., 2015; Guimarães Nobre et al., 2019; Staupe-Delgado and Kruke, 2017; Weingartner et al., 2020). Whilst the emergence of new management terms is likely to attract renewed investment for DRM (Meadowcroft and Fiorino, 2017; Simion and Kelp, 2019), the risks of these terms creating conceptual and operational redundancies with traditional management terminologies has not been assessed for drought (Bosher et al., 2021; Staupe-Delgado and Kruke, 2018). Inconsistencies among DRM conceptual frameworks can inhibit coordinated management, and they are considered a potential further barrier to drought management (Rosch, 1973; Bosher et al., 2021; Sawalha, 2020; Staupe-Delgado and Kruke, 2018; Kuhlicke et al., 2023).

Identifying a renewed feasibility of water monitoring systems, as well as knowledge gaps about the system-level value of the data, its applications for drought DRM, and the barriers to the data's collection, my research abductively focusses on the issue of data scarcity in WRM and drought DRM (Saunders et al., 2019). I use systems theory as an analytical framework to assess

the relationships between water data and other components of the coupled human-water system (Konar et al., 2019). In considerations of 'value', I implicitly use the UN Sustainable Development Goals (SDGs) analytical framework as a suitable qualitative metric (UN DESA, 2022). My study's design is underpinned by the philosophy of pragmatism, given its problem-oriented and inter-disciplinary focus (Dewey et al., 1925; Doyle et al., 2009; Peirce et al., 1878; Saunders et al., 2019). In the chapters, mixed-methods are used to generate conclusions that consider both the technical and sociological elements of the systems under study (Doyle et al., 2009; Saunders et al., 2019).

1.2 Study Region

Somalia and its neighbouring Horn of Africa states (Ethiopia, Kenya, Djibouti, Eritrea, Uganda, Sudan, South Sudan) experience difficult WRM and DRM challenges (Thomas et al., 2020). The Arid and Semi-Arid Lands (ASALs) in the region have a high occurrence of drought due to low rainfall volumes, high rainfall variabilities, growing water demands and weak water supply infrastructure (Adloff et al., 2022; King-Okumu et al., 2019; Liebmann et al., 2014; Mwadalu and Mwangi, 2013). Across the Horn of Africa, groundwater is the principal source of potable water during dry seasons, and its equitable management is key to maintaining year-round, drought-resilient water security for most of the population (Adloff et al., 2022; Braune and Xu, 2010; MacDonald et al., 2012; Pavelic et al., 2012; Thomas et al., 2020).

Most rural livelihoods across the states in the Horn of Africa depend on farming and related activities (Huho et al., 2011; Little, 2013). In the arid regions of Somalia, northeast Ethiopia and northeast Kenya, all home to the Somali ethnic group, nomadic pastoralism is the predominant livelihood, comprising 55% of Somalia's total population (IGAD, 2023; Opitz-Stapleton et al., 2022). Nomadic pastoralism is less common in semi-arid, riverine and more humid rural areas, where agro-pastoralism and agriculturalism cultivating grains, sugarcane, cotton, fruit and vegetables are the main farming livelihoods (Massey, 2019). In the humid and tropical biomes, where water shortages are less acute, agriculturalism is predominant and cash crops are common (Paul et al., 2020a). Most agriculture in the region is rain-fed and vulnerable to yield shortages during drought (Headey et al., 2012; Paul et al., 2020a), however, the highest

risk of rural water and food insecurity due to drought is in ASALs (Krampe et al., 2020; Little, 2013).

In ASALs, nomadic pastoral and subsistence livelihoods are especially vulnerable to drought impacts due to rainfall-dependencies, a high risk of land conflicts and limited access to services, markets and aid (Headey et al., 2012; Huho et al., 2011; Gumucio et al., 2022; Little, 2013; Nelson et al., 2020; Opitz-Stapleton et al., 2022). However, food insecurity and displacement among agro-pastoral households and communities is also common during droughts when rain-fed agricultural yields decline (Headey et al., 2012; Krampe et al., 2020). Despite the differences in climate and livelihoods across the Horn of Africa's rural areas, many of the challenges of WRM are similar (Bjornlund et al., 2020; Hughes, 2019; Thomas et al., 2020; UNESCO, 2021; UN-Water, 2022). Water is supplied through a varying combination of community water committees, private suppliers, informal markets, formal markets, government projects, self-supply and Non-Governmental Organisations (NGOs; Adams et al., 2019; Foster et al., 2018; Hashi et al., 2016; Klassert et al., 2023). Whilst these water supply systems largely meet water security needs during periods of non-drought and non-conflict, each of these infrastructures are vulnerable to sudden changes in supply or demand (Thomas et al., 2020; Foster et al., 2018). When water supply systems become stressed, it is typically the poorest rural households that will experience water and food insecurity when they are unable to cover their increasing costs or afford alternative means of access (Gumucio et al., 2022; Huho et al., 2011; Krampe et al., 2020).

All states in the Horn of Africa are experiencing rapid urbanisation (Yeboua and Cilliers, 2021). The most vulnerable to water and food insecurity in urban areas are Internally Displaced People (IDPs; Adeyeye et al., 2020; Regasa et al., 2023). A high proportion of IDPs are women and children who have been displaced from their habitual residence and who often lack access to income, assets, social networks or services (Regasa et al., 2023). In stronger states such as Kenya and Ethiopia, the government water authority or dedicated local water utility(s) is partly responsible for formal urban water supply, operating piped networks, distribution points and water trucking (Gaye and Tindimugaya, 2019). However, areas of informal housing depend heavily on the informal water sector, supplied by privately owned boreholes or water trucking (Adeyeye et al., 2020; Klassert et al., 2023; Neal, 2020). This is the case across the Horn of Africa, though the importance of the private and informal water sector is greater in weaker states such as Somalia (Klassert et al., 2023). Intense urban abstraction is causing a long-term

annual decline of aquifer water levels in many cities (Gaye and Tindimugaya, 2019). During droughts, water availability shortages are less common in urban areas than rural areas due to the quantity of water suppliers and proximity to government and non-governmental services (Gaye and Tindimugaya, 2019; Krampe et al., 2020; Little, 2013). However, water insecurity is often experienced by households through price increases that can exceed the purchasing power of the poorest (Huho et al., 2011; Neal, 2020).

The role and capabilities of the state in managing water and food security varies (Gaye and Tindimugaya, 2019; Krampe et al., 2020). Where there has been sustained, stable governance, such as in Djibouti and Kenya, tax collection, government creditworthiness and established government institutions means that they can coordinate the management of water and food security (Krampe et al., 2020). Kenya, for example, has a dedicated National Disaster Management Authority (NDMA) leading the management of drought emergencies (Bowell et al., 2021). In these states, the humanitarian sector largely adopts a supporting role on government-led development strategies. In contrast, where there is weak or unstable national state governance, responsibilities for ensuring water and food security partly belongs to other stakeholders (Gavin et al., 2019; Hussein et al., 2021). For example, in Somalia, the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) adopts a leading role in the coordination of development and disaster response plans due to weak state capacities, especially in disputed territories and areas of active civil conflict (Ahmed et al., 2020; Gavin et al., 2019; Mourad, 2023). In Tigray, Ethiopia, disputed governance of the territory means the federal Ministry of Water and Energy has a reduced capacity and presence in the region (Abay et al., 2022; Mach et al., 2019). In areas of conflict, such as during the 2020 – 2022 Tigray war, temporary management of water resources can become a challenging shared responsibility between humanitarian stakeholders, private suppliers, local water utilities and communities (Abay et al., 2022). Conflicts can impact water supply through equipment and staffing shortages, damaged infrastructure, sudden increases in water demand, cost increases, corruption of water resources, discontinued development projects and discontinuations of regular governance (Krampe et al., 2020; Solomon et al., 2018). Humanitarian access to the most vulnerable can be challenging (Gumucio et al., 2022; Hussein et al., 2021), and humanitarian support focalises in stable urban centres or dedicated IDP camps that become migration sinks for IDPs (Krampe et al., 2020; Nelson et al., 2020). Conflicts are a major driver of water and food insecurity crises in the Horn of Africa, and they significantly complicate the challenges of WRM (Opitz-Stapleton et al., 2022; Solomon et al., 2018).

My research, in evaluating knowledge gaps relating to water monitoring for WRM and DRM, focusses on the Horn of Africa as a socio-economically, politically and environmentally diverse region with many shared water management challenges (Hughes, 2019; Larsson, 2009; UNESCO, 2021; UN-Water, 2022). Conducting the study at a regional scale of focus reflects the regional scope of many key humanitarian stakeholders in the Horn of Africa, including my project partners at the Foreign United Kingdom Commonwealth and Development Office (FCDO), the Building Resilient Communities in Somalia Consortium (BRCiS), Concern Worldwide and the United Nations Food and Agricultural Organisation (FAO), who coordinate regional budgets and activities from offices located in Nairobi. The research's focus on humanitarian issues narrows its focus to primarily consider the areas and communities most vulnerable to water and food insecurity, i.e. rural ASALs, IDPs and those requiring humanitarian assistance in urban areas (Gumucio et al., 2020). The research also focusses on the self-declared independent republic of Somaliland to study system processes at a more local context, following partnerships made with Concern Worldwide, Somaliland's Ministry of Water Resources Development (MoWRD), and the FAO's Somalia Water and Land Information Management (SWALIM) unit. Groundwater monitoring activities and some targeted snowball sampling of stakeholder interviews in the study are located in Maroodi Jeex, Somaliland. Maroodi Jeex includes the capital city of Hargeisa, its densely populated rural-urban fringe and many sparsely populated semi-arid and arid areas, hosting a range of agricultural, agro-pastoral and nomadic pastoral livelihoods (Abdulahi, 2021). The region was suitable for fieldwork given its long-term political security and accessibility for rural groundwater monitoring and stakeholder interviews. Whilst local WRM processes significantly differ across the Horn of Africa, the diverse district of Maroodi Jeex and neighbouring districts in Somaliland comprise some of the most vulnerable areas to water and food insecurity, with many of its local DRM, WRM and data scarcity challenges shared with other ASALs in the Horn of Africa (Hughes, 2019; Gaye and Tindimugaya, 2018; Guimarães Nobre et al., 2019; MacDonald and Calow, 2009; Maxwell et al., 2021; UNESCO, 2021; UN-Water, 2022; Ahmed et al., 2020; Gavin et al., 2019; Mourad, 2023).

1.3 Aims and Research Objectives

This study principally aims to advance our understanding of the issue of data scarcity in WRM, by assessing the potential applications and benefits of water monitoring data, the causes of its continued scarcity and actionable solutions to those causes. The themes of drought, groundwater and the region of the Horn of Africa are used as focal points in the research, as their nexus represents a case study where the consequences of data scarcity are especially acute (Gaye and Tindimugaya, 2018; Guimarães Nobre et al., 2019; Maxwell et al., 2021; UNESCO, 2021; UN-Water, 2022). The research chapters and conclusions aim to address 5 key objectives:

***Objective 1*:** To evaluate the barriers to drought-resilient water resources management (WRM) in low- and middle-income countries [Chapter 3].

Objective 2: To determine stakeholder information needs for proactive drought and water resource management [Chapter 3].

Objective 3: To assess whether conceptual barriers in drought DRM can be addressed by conceptual innovations [Chapter 4].

Objective 4: To qualitatively assess the applications and benefits of high-resolution water monitoring data [Chapters 3, 5 & 6].

Objective 5: To assess the causes of water monitoring data scarcity and how they can be resolved [Chapters 5 & 6].

1.4 Thesis Structure

This thesis is structured to sequentially address the study's research objectives, though some objectives overlap multiple chapters. Chapters 3 – 6 are written in a standard scientific format for publication, followed by a discussion (Chapter 7) and conclusion (Chapter 8) that integrate and conclude the findings from the preceding five chapters. The content of each chapter is outlined and linked to the research objectives it seeks to address (Figure 1.1).

1.4.1 Chapter 2: Methods

The methods are compiled ahead of the research chapters to introduce their rationale and avoid repetition where the interview data is used in Chapters 3, 4 and 6. The chapter details the research sequencing and impact of the Covid-19 pandemic; the interview methods including sampling, ethical procedures and methods of analysis and data presentation; the background to the groundwater monitoring data used in Chapters 4 and 5; the narrative literature review performed in Chapter 4; and the research philosophy and methods of data presentation throughout the thesis.

1.4.2 Chapter 3: Proactive Drought Management Needs Water Security Data

Chapter 3 first addresses Research Objective 1, by assessing the barriers to drought and water resources management through inductive semi-structured interviews of expert stakeholders during the 2021 – 2023 Horn of Africa drought. After framing data scarcity barriers within the wider system of management barriers, the chapter addresses Research Objective 2 by evaluating stakeholder information needs for improved drought management outcomes. The results identify information needs centring upon water security monitoring data, so the potential role of these data in resolving the identified management barriers is discussed (Research Objective 4). I then pragmatically organise the findings into conceptual diagrams that illustrate the potential for water security data to index the rapid financing of proactive, drought-mitigating interventions. The chapter is written for a primarily humanitarian and policy-focussed target audience, intended for publication in Nature Sustainability, Food Security or another interdisciplinary, policy-oriented journal.

1.4.3 Chapter 4: Updating the Drought Management Framework

Chapter 4 addresses Research Objective 3. The chapter methods and objectives were designed abductively, following the emergent findings of conceptual barriers to drought and disaster risk management (DRM) in Chapter 3 (Saunders et al., 2019). In this chapter, I assess the theoretical paradigms in DRM and the extent to which they reflect the operational objectives and realities of drought management. I use a multiple methods approach (Doyle et al., 2009), using a narrative literature review to identify paradigms and the findings from groundwater monitoring and semi-structured expert interviews to evaluate them. The chapter identifies conceptual

issues in applying traditional DRM terminology to droughts in practice, while finding that the conceptual innovations of 'anticipatory action' and 'resilience building' more clearly describe realities and objectives in drought DRM. It proposes a pragmatic convergence to an updated drought management framework, intended to advance a more common understanding of drought management for scientists, policymakers and other stakeholders in drought management. The chapter is written for a broad, non-specialised target audience, given its objective of clarifying an understanding of drought and DRM language across different stakeholder groups.

1.4.4 Chapter 5: Localizing Hydrological Drought Early Warning Using In Situ Groundwater Sensors

Chapter 5 is a quantitative study, assessing the technical feasibility of upscaling groundwater monitoring systems (towards Objective 5), as well as the policymaker-relevant outputs that can be processed and analysed from groundwater level data (towards Objective 4). The chapter presents methods for analysing short groundwater data datasets in resource-scarce settings where the long-term collection of groundwater observations is challenging. The modelling approach presented in the chapter enables calibrated well water level simulations to be set up following monitoring periods of just weeks-months. The use of a pragmatic modelling method is intended to facilitate the rapid setup of upscaled monitoring systems, where a large number of wells can be simulated following short monitoring periods. The chapter proposes contextualised outputs from the data for humanitarian and WRM audiences, addressing the shortage of confident, contextualised drought early warning information that is identified in Chapter 3. This work is published in Water Resources Research with supporting co-authors (Veness et al., 2022; doi: 10.1029/2022WR032165).

1.4.5 Chapter 6: Unlocking the Benefits of Groundwater Data

Chapter 6 qualitatively assesses the benefits of high-resolution groundwater monitoring networks in the Horn of Africa through semi-structured expert interviews (Objective 4). The considerations of benefits and value are qualitative, rather than quantitative, as it is important to first inductively establish the scope of potential data users, their data applications and the nature of the data's value to users. The interviews identify benefits to 18 different stakeholder groups, after which the barriers to groundwater monitoring and expert-guided solutions to those

barriers are assessed (Objective 5). The chapter concludes by constructing a 5-stage framework for sustainably scaling decision-integrated groundwater monitoring systems, intended as a guide for policymakers and WRM practitioners. Beyond its academic contributions centred on groundwater data, the chapter provides a simple template for a qualitative stakeholder scoping method that is reproducible for other hydrological variables and locational contexts.

1.4.6 Chapter 7: Discussion

Chapter 7 hosts a reflective discussion regarding the inter-relationships between the respective chapters, as well as the limitations, confidence and generalisability of the findings and the other considerations for attracting water monitoring investment that are not explicitly discussed in the preceding chapters. It extends the discussion of the thesis' contribution to the objective of resolving data scarcity in WRM, and it clarifies cautions of limitations to the reader to help with interpreting the confidence and wider relevance of the findings.

1.4.7 Chapter 8: Conclusions and Outlook

Chapter 8 presents the study conclusions and research outlook. In this section, I present the main academic contributions of the preceding chapters and consider their collective contribution towards the wider issue of resolving data scarcity in WRM. It concludes with an academic research outlook in which 27 further knowledge gaps relevant to the issue of data scarcity are detailed.

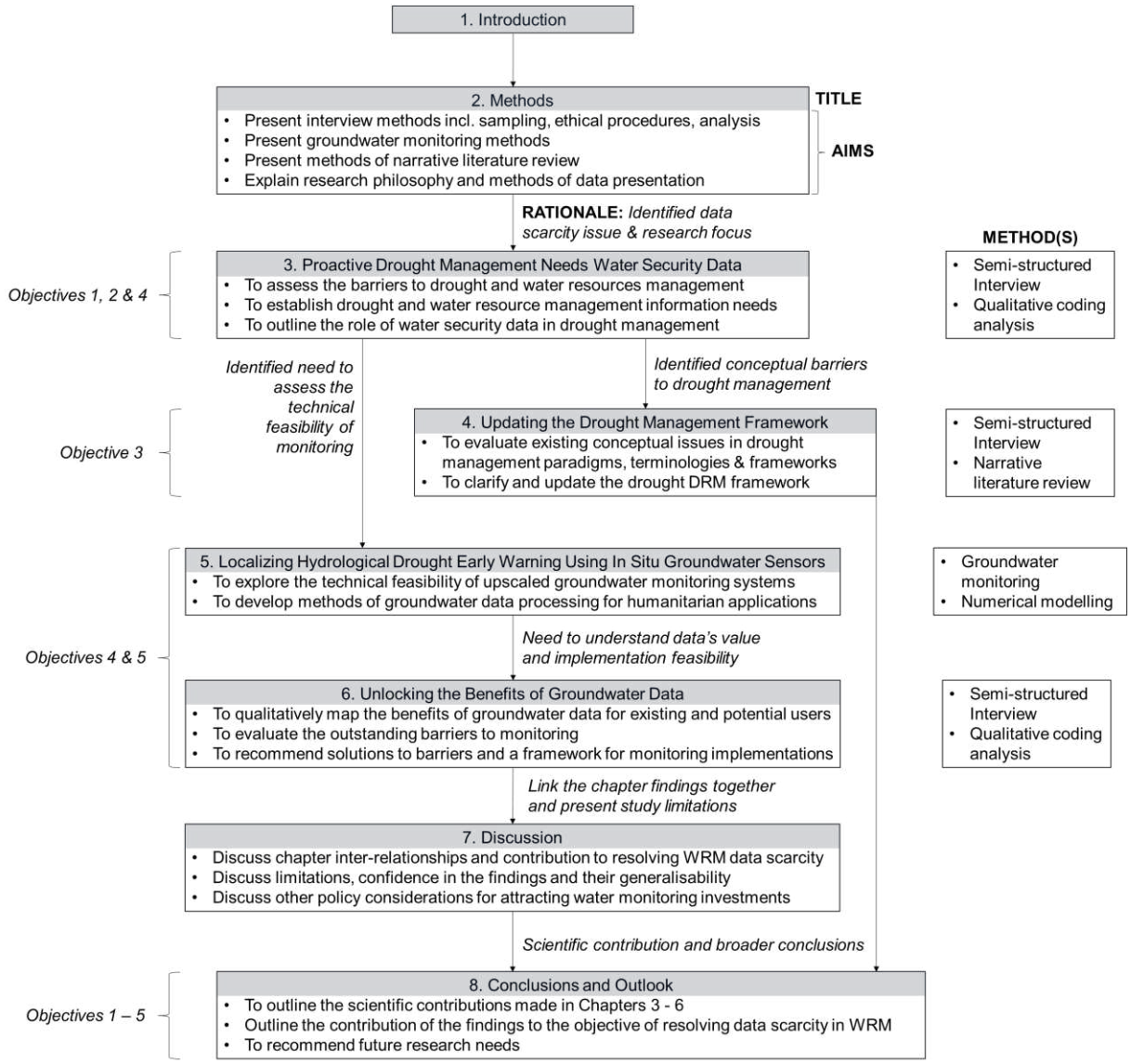


Figure 1.1. Outline of the thesis chapters' content, aims, rationale and methods.

2 Methods

2.1 Overview

Data scarcity and related issues in WRM and DRM are practical research problems best suited to a pragmatic philosophical approach (Dewey et al., 1925; Doyle et al., 2009; Peirce et al., 1878; Saunders et al., 2019). This approach accommodates the use of mixed quantitative and qualitative methods that consider both the technical elements of data collection, processing and analysis, as well as the qualitative elements of monitoring systems such as user-centred design, governance and data presentation (Doyle et al., 2009, Saunders et al., 2019). Semi-structured expert stakeholder interviews were the primary method of data collection for Chapters 3, 4 and 6 (Chapter 2.3). Groundwater monitoring data in Maroodi Jeex and Borama, Somaliland was collected with project partners Concern Worldwide and UN FAO SWALIM for analysis in Chapters 4 and 5 (Chapter 2.4), and Chapter 4 further uses results from a targeted narrative literature review in its analysis sections (Chapter 2.5).

2.2 Research Sequencing

The sequence of research stages differed from the original research plan, following external disruptions caused by the Covid-19 pandemic and a concurrent humanitarian crisis due to drought in the Horn of Africa (OCHA, 2021a; UNHCR, 2021). I initially intended to complete qualitative interviews and quantitative methods concurrently, so that quantitative methods of groundwater data analysis and presentation would incorporate the important principle of user-centred design (Maxwell et al., 2021; Zulkafli et al., 2017). I had equally planned with project partners to monitor a minimum of 15 groundwater monitoring stations for multi-year time series, accompanied by extensive community consultations and interviews. Substantial delays

to field visits in Somaliland continuously postponed methods towards these objectives until they became no longer viable due to time constraints and operational restructuring within our partner institutions.

Prohibited travel to most African countries cancelled planned fieldwork to Hargeisa and Borama in April 2020. Following incremental delays, the field visit to Hargeisa and Maroodi Jeex instead took place in November 2021, over 2 years after the project's start date in September 2019. The compressed timeline and the challenge of engaging WRM stakeholders in Somaliland, who were occupied with emergency drought responses throughout 2022, led me to abandon plans for further groundwater monitoring.

To adapt the project, I spent the first 2 years developing Chapter 5, using data previously collected by project partners Concern Worldwide in 2017. Although the associated publication in Water Resources Research was unable to incorporate planned methods of user-centred design, the findings nonetheless provide an important advancement in the methods of groundwater monitoring system design in resource-scarce contexts (Veness et al., 2022). The continued difficulties of access and stakeholder engagement in Somaliland and Somalia motivated the expansion of stakeholder interviews to include regional expert stakeholders in drought and water resources management. Interviews were conducted online or during field visits to Maroodi Jeex, Somaliland in November 2021, Kampala, Uganda in June 2022 and Nairobi, Kenya in July 2022. Whilst the Horn of Africa drought disrupted initial research plans, the event created a unique opportunity to interview stakeholders during the management of a real-time drought event, benefitting the depth and accuracy of interview responses (Tuckey and Brewer, 2003). The interviews assessed information needs for drought management (Chapter 3) and the benefits, challenges and solutions for groundwater data collection (Chapter 6) as originally planned. The interviews also yielded emergent findings relevant to the conceptualisation of drought DRM, which motivated the development of Chapter 4 through a narrative literature review and further qualitative interview analysis at the end of the project.

2.3 Semi-Structured Interviews

2.3.1 Interview Design

Prior to the interview's design, literature reviews and unstructured discussions with drought stakeholders were used to establish objectives, methods and potential questions for the interviews (Saldana, 2021). A semi-structured interview topic guide was then designed to collect qualitative perspectives from 42 expert participants for analysis in Chapters 3, 4 and 6 (Galletta, 2013; Gumucio et al., 2021; Brinkmann and Kvale, 2018; Patton, 2015; O'Keeffe et al., 2016). Using a semi-structured template creates a consistent interview structure for key questions to be consistently addressed, and it ensures that answers to specific questions can be analysed as an entity, whilst remaining open enough for emergent information to arise and be interrogated through discussion (Galletta, 2013; Mojtahed et al., 2014). Given the specialist expertise and diverse perspectives among the expert participants in this study (Figure 2.1), this was pragmatic for pursuing emergent information through multiple follow-up questions (Galletta, 2013; Mojtahed et al., 2014). The two-way, discursive nature of the interviews ensured an interview style that emulated regular conversation, and it supported the co-construction of findings between interviewer and participant based on their subjective experiences (Patton, 2015, Mojtahed et al., 2014; Creswell, 2009; Mills et al., 2006).

For Chapter 3, Part 1 of the interview collected expert perspectives on drought management barriers and stakeholder information needs for improved management. For Chapter 4, responses to these same questions were assessed alongside a narrative literature review to evaluate whether conceptual paradigms in drought DRM are reflected in practical accounts of management processes. For Chapter 6, Part 2 of the interview collected expert perspectives on the benefits of groundwater data and expert recommendations for successful future monitoring implementations. In Part 2, for the 22 interviewees who had worked with groundwater data before, their responses provided an ex-post assessment of their experiences with groundwater data. Whereas for the 20 participants with no prior experience of groundwater monitoring data, their perspectives offered an ex-ante assessment of groundwater data's potential value to them and others, in a scenario where networks of monitoring data are routinely collected, processed and accessible to stakeholders (Samset and Christensen, 2017). The capturing of ex-ante and ex-post perspectives for the same questions was a pragmatic choice to assess the benefits and

applications of groundwater data for its full range of potential users (Samset and Christensen, 2017).

Part 1 – Drought Management

1. What is your professional role and experience?

2. What are the barriers to better management of droughts?

3. What information do you use for early warning and monitoring of droughts?

4. What evidence do you need to take drought management actions? What early actions do you and/or your institution take?

5. What evidence do you need to release funding of drought-associated actions at your institution? (if relevant)

6. Do existing information sources meet your/your colleagues' information needs?

7. What further information would improve your/others' actions taken? How?

Part 2 – Groundwater Data

8. Have you worked with groundwater data before?

[if no – a 5-minute explanation of groundwater monitoring basics and example projects given]

9. Do you believe that access to groundwater monitoring data would be useful? Would it have beneficial value for you or other stakeholders? If so, how?

10. What outstanding challenges do you foresee for setting up sustainable groundwater monitoring systems that are integrated into decision making?

11. How should such a system be setup and be governed for it to be successful?

12. How should groundwater data be presented?

2.3.2 Ethical Procedures

The research study was reviewed and approved by the Head of the Department of Civil and Environmental Engineering and Imperial College London's internal Science Engineering

Technology Research Ethics Committee, according to Imperial College London's research requirements (SETREC; case number 21IC6694). The application comprised a clear research protocol, an information sheet and consent form for participants, an interview template and details about sampling approaches, which were reviewed by the Research Governance and Integrity Team. The information sheet was sent to participants for review prior to their signing of the consent form. The information sheet explained the purpose of the study, why they were invited to take part, the voluntary nature of participation, the right to withdraw interview responses within one month of completion, the anonymisation of interview responses, the potential risks of taking part, the management of participant data, the funding of the project, and contact details for any future questions or requests regarding the research. Prior to each interview, the key details from the participant information sheet were repeated to ensure that they were understood by the participant before commencing the interview. Following the interviews, all interview data was stored safely in a password protected repository. Interview audio recordings were deleted immediately following transcription, and personal details were removed from interview transcripts to anonymise participants during data analysis.

2.3.3 Interview Sampling

Snowball sampling began with key informants, using contacts provided by project partners Concern Worldwide, the United Kingdom's Foreign Commonwealth and Development Office (FCDO), the Norwegian Refugee Council (NRC), the Building Resilient Communities in Somalia Consortium (BRCiS), the Ministry of Water Resources Development in Somaliland, and the United Nations Food and Agricultural Organization's Somalia Water and Land Information Management unit (UN FAO SWALIM). All participants had at least 5 years of professional or academic experience in the Horn of Africa, with over half of interviewees having at least 20 years' experience. All participants selected were actively studying or managing water, food, governance or humanitarian activities in the Horn of Africa during the 2022 drought, though many experts from NGO, UN, Academia and Private cases also drew upon global experiences of droughts and WRM in their responses. Snowball sampling purposefully targeted experts from diverse backgrounds, with efforts made to include a range of profession-cases to capture a participant population representative of the main expert stakeholder groups in WRM, drought governance and the humanitarian sector in the Horn of Africa (Gumucio et al., 2021). Sections 2.3.3.1 – 2.3.3.3 describe the sampled participant

categories in detail. Whilst the 42 interviewees captured perspectives from across the Horn of Africa, actively working or researching in Somalia, Somaliland, Kenya, Ethiopia, Uganda and South Sudan, 30 participants had experience working in Somaliland and 14 were based there full time. As such, Somaliland and Somalia have a greater representation in the research findings, especially in the sections focussed on local or district level stakeholders. Interview sampling was discontinued once the amount of new information arising from answers became low (Galletta, 2013; Saldana, 2021). Interviews took place in-person or via video conferencing software Microsoft Teams, with all interviews recorded, transcribed using Otter.ai and anonymised, before qualitative coding analysis using NVivo.

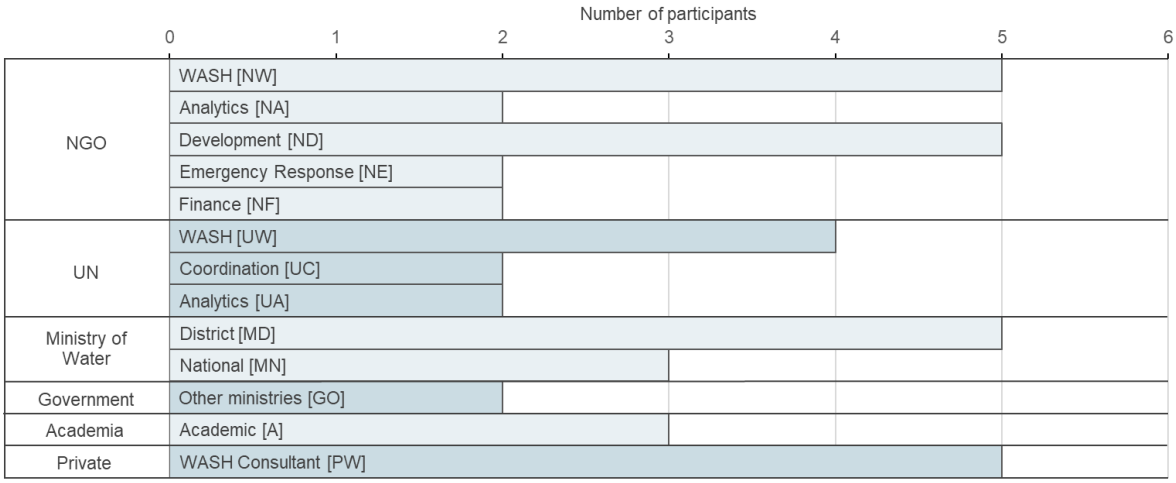


Figure 2.1. Professional roles of the 42 study participants. The profession reference codes used to anonymise interviewees in the analysis of Chapters 3, 4 and 6 are shown for each role.

2.3.3.1 NGO & UN

Non-Governmental Organisation (NGO) and United Nations (UN) Water Sanitation and Hygiene (WASH) teams support national water authorities in achieving WASH development objectives, often bringing technical expertise and financial capacity that are missing in the institutions that they support. Their objectives align with SDG 6 – clean water access for all (UN-Water, 2021b). They have a more prominent role in areas of conflict or internally displaced person (IDP) camps to ensure that water is provided to those that cannot afford it.

NGO/UN analytics teams create value out of physical and socio-economic humanitarian data by turning raw data into outputs and insights that can guide humanitarian, public, private and

government decision making. These teams are growing, with prominent examples of the FAO's Food Security Nutrition and Analysis Unit (FSNAU), the Famine Early Warning Systems Network (FEWS NET), and the Humanitarian Data Exchange (HdX), but their outputs have been criticised for poor communication and failure to tailor outputs to stakeholder needs (Maxwell et al., 2021).

Development, coordination and emergency respondents often have broader objectives of working towards all SDGs in their activities. For development workers this ranges from implementing long-term projects such as female-led microenterprises through to investing in more resilient WASH systems, as projects are designed to local needs. Emergency responders, in contrast, will be deployed on short-term bases when lifestyles are disrupted following crises such as floods, droughts, locust outbreaks and civil conflicts.

Humanitarian finance teams control budgets from mixed sources and operate at a national or regional scale. These stakeholders are interested in data sources that can improve the accuracy of decision making to ensure the correct projects are funded to meet local objectives and need.

2.3.3.2 Water Authorities and Government

National water authorities, often termed ministries, vary in technical, financial and staffing capacity between states, though all of them are formally the lead body in coordinating national water resource management. As a public body they report to politicians and the public, so follow the primary objective of optimising water resource management for the public good. In contrast to NGO and UN WASH professionals, the national authority can enforce government legislation on the public and the private sector when required.

The district water authority and governance of water resources varies between geographies. In states with stronger governance, this may be a district office of the national water authority, a dedicated river basin authority or an urban water utility. In areas of weaker state-governance, this may be a self-organised private or community-owned network. Whether for profit or public service, these institutions' primary interest is the maintenance of reliable supply, and they have extensive local knowledge, experience and contacts. In the Horn of Africa, these tend to be district arms of the national water authority, and these were interviewed in Somaliland, Kenya, Uganda and Ethiopia in this study.

Other government departments, such as departments of planning, development and agriculture are also interested in water resource management, as it affects their ability to meet their own objectives. Representatives from these are frequently drawn into emergency disaster committees during times of drought or other crises to collaboratively design emergency response plans.

2.3.3.3 Academia and Private Consultants

Academic and private consultant experts in WASH, DRM and WRM have a combination of core knowledge, expertise and experience that provides rich insight in interview. The academics in this study were both locally and internationally based, while the expert consultants interviewed had a minimum of 15 years' experience of WASH in the Horn of Africa.

2.3.4 Qualitative Analysis

Thematic qualitative coding analysis of the interview data for Chapters 3 and 6 used an inductive coding approach for all questions (Patton, 2015; Saldana, 2021). Interpretive codes were assigned to key question-relevant information within the interview transcriptions and organised into emergent themes of related codes. The first round of qualitative coding was completed concurrently with interview data collection to highlight information gaps in the thematic analysis that could be targeted through subsequent focussing of the sampling and questioning (Saldana, 2021). Three rounds of coding were completed to standardise codes, sub-themes and themes across the analysis (Saldana, 2021).

During thematic analysis, the diversity of participants' professional experiences (Figure 2.1) produced emergent findings on topics broader than those initially targeted by the semi-structured template, including topics of drought DRM definitions and applications (Galletta, 2013; Patton, 2015; Creswell, 2009). Furthermore, their diverse backgrounds caused variation in their applications and understanding of common drought and DRM terminologies (Mojtahed et al., 2014). This incentivised a transition from an inductive to an abductive approach for the coding in Chapter 4, where additional coding themes recorded cases where participants applied these terms or explicitly discussed them (Saunders et al., 2015). Therefore, new codes relating

to drought and DRM definitions were assigned during the 2nd round of coding (Saldana, 2021), and a 3rd round of coding standardised these classifications across all interviews.

2.3.5 Interview Data Presentation

Many of the results from the interview analysis are presented in Chapters 3, 4 and 6 as thematic plots. Some of these quantify the number of participants referencing certain codes, themes or sub-themes in the analysis (Figures 3.3, 3.4, 6.4), whilst Figure 6.1 maps codes to stakeholders that stated them, and Table 4.1 maps qualitative codes to a framework (UNDRR, 2015; UNDRR, 2016). In subsequent analysis and discussion sections in Chapters 3, 4 and 6, conceptual diagrams (Figures 3.5, 3.6, 4.4, 4.5, 6.2, 6.4) have been constructed to best communicate key interpretive findings from the thematic coding analysis (Patton, 2015; Mills et al., 2006). These figures are described as conceptual diagrams in their captions to distinguish them from the thematic plots presenting the results of the thematic analysis. They are constructed based on my subjective interpretation of the preceding findings as the interviewer and lone analyst of the data (Mills et al., 2006; Mojtahed et al., 2014), and they are a pragmatic addition to the discussions to communicate my interpretations and their implications. The designs of the conceptual diagrams all received iterative feedback from multiple research colleagues and at least one of the expert study participants before they were finalised (Thomas, 2016).

2.4 Groundwater Monitoring

In Chapter 4, Figure 4.3 supports the analysis of drought definitions, presenting groundwater level data shared by the United Nations' Food and Agricultural Organization's Somalia Water and Land Information Management Unit with permissions for research use (UN FAO SWALIM; SWALIM, 2023). The observation borehole in Hargeisa, Somaliland (Figure 4.3a) is a 90 m depth borehole of 4 cm diameter in Geed Deeble village. The abstraction borehole in Borama, Somaliland (Figure 4.3b) is 84 m depth and of the same diameter. The wells were monitored at 12-hour intervals by commercial pressure transducers, installed 2 m above the height of the pump intake. In Chapter 5, groundwater monitoring installations led by the NGO Concern Worldwide contributed data from 3 shallow wells in Maroodi Jeex, Somaliland as

inputs for groundwater modelling. The wells each provided a 30-week time series of data using commercial pressure transducers collecting readings at 15-minute intervals. The full methods of data collection, processing and analysis used in Chapter 5 are detailed separately within the chapter (Chapter 5.2).

2.5 Narrative Literature Review: Chapter 4

The emergence of DRM-terminology themes during thematic analysis for Chapter 4 incentivised a pragmatic, concurrent narrative literature review to establish existing frameworks, definitions and paradigm applications (Baumeister and Leary, 1997; Green et al., 2006; Kuhlicke et al., 2023; Saunders et al., 2015). Thus, Chapter 4 uses multiple qualitative methods to inform its results and discussion (Chamberlain et al., 2011; Collier and Elman, 2008; Sherrod, 2006). This pluralistic approach enables conclusions that the interview data alone would not be able to construct in isolation (Doyle et al., 2009; Sherrod, 2006; Chamberlain et al., 2011; Collier and Elman, 2008). In the chapter, the narrative review identifies paradigm definitions and frameworks in drought management and DRM, then both the interview data and articles from the literature review are used to critically assess the extent to which they reflect operational objectives and realities in practice (Cantelmi et al., 2021; Sherrod, 2006). This study is therefore a commentary-style narrative review, where critical analysis of the literature is supported by evidence from the interview data (Green et al., 2006; Patton, 2015). A narrative review was preferred to a systematic review due to the diversity of DRM themes discussed, the under-representation of emergent themes such as 'anticipatory action' in academic literature (Baumeister and Leary, 1997; Green et al., 2006), and the importance of grey literature, with no collective repository, in establishing paradigms in DRM using best-evidence (Adams et al., 2017; Haddaway et al., 2015; Green et al., 2006).

2.6 Analysis and Discussion

The analysis and discussion sections in the chapters guided by the pragmatic research paradigm, with an ontology that reality is reflected primarily by the practical consequences of both objectively measurable phenomena and subjective ideas in combination (Doyle et al.,

2009; Kuhlicke et al., 2023; Peirce, 1878; Rosch, 1973; Saunders et al., 2015; Saunders et al., 2019). It is problem-oriented in its epistemology, interpreting both quantitative and qualitative evidence-bases collectively in seeking an understanding and solution to practical issues within drought and water resources management (Doyle et al., 2009; Green et al., 2006; Saunders et al., 2019). Whilst Chapter 5 takes a more positivist approach than the interpretivist methods applied in Chapters 3, 4 and 6, it remains pragmatic in its context-appropriate approach to groundwater modelling. The pragmatic approach of Chapter 5 is what provides much of its scientific novelty from positivist hydrological modelling literature, as it confronts the practical trade-off between modelling confidence and implementation feasibility (Beven, 2001, Beven, 1989, Maxwell et al., 2021; Nature Sustainability, 2021). The objectives, analysis and discussion in all chapters focus on upon solutions to practical problems, and as such they are written primarily for policy-oriented research audiences

‘

.

3 Proactive Drought Management Needs Water Security Data

3.1 Abstract

Drought is a primary driver of humanitarian crises in the Horn of Africa, yet indicators of water insecurity remain absent from humanitarian Early Warning Systems (EWSs). The 2021 – 2023 Horn of Africa drought caused 43,000 excess deaths in Somalia during 2022 alone, with unmitigated water supply failures leaving 23% of its population acutely water insecure. Here, interviews completed during the drought with 42 regional experts are used to evaluate the barriers to management and whether existing information systems are meeting stakeholder information needs. The study finds water security data scarcity to be a barrier to financing humanitarian interventions, as there is insufficient data to predict how drought will translate into socio-economic impacts. Most investment decisions are triggered instead by indicators of food security hosted by EWSs, which exceed thresholds at long lag times following physical drought onset. Over 75% of experts describe water security data information needs. Local water availability monitoring of groundwater and surface sources, and water access monitoring through water prices and household surveys can guide the planning of drought impact-mitigating interventions such as borehole rehabilitation, technical support, emergency water supply and cash transfers. Furthermore, if the causal relationships between water insecurity and food insecurity are analysed from the data, local water insecurity indices can become confident predictors of local food insecurity to index associated anticipatory actions. Value propositioning ex-ante projects using more confident, local predictive data can use positive economic and social returns on investment to attract both traditional and new, innovative index-based sources of humanitarian finance.

3.2 Introduction

3.2.1 Droughts, Early Warning and Early Action

Underfinanced humanitarian responses to droughts, most notably during Somalia's 2011 drought and famine, have prompted international calls for their management to shift from reactive to proactive approaches (Hillbruner and Moloney, 2012; Maxwell and Majid, 2016; Sivakumar et al., 2014). Early Warning Systems (EWSs) have been developed to support this process, which host monitoring evidence-bases for planning and financing humanitarian interventions. EWSs are now established as the principal information source for food security monitoring and forecasting in Sub Saharan Africa (Andree et al., 2020; Farr et al., 2022; Funk et al., 2019; Maxwell and Majid, 2016; Maxwell et al., 2021). Through these information systems, international organisations, governments and other stakeholders trigger finance for management actions when indicators exceed threshold levels (CERF, 2022; Maxwell et al., 2023; Otkin et al., 2022).

Management actions guided by these systems are commonly described as 'early actions' or 'anticipatory actions', which have demonstrated substantially improved economic and social returns on investment compared to traditional humanitarian drought response (Cabot Venton, 2018; Cabot Venton et al., 2013; Costella et al., 2017; UNICEF, 2015; Clarke and Vargas Hill, 2013; Hallegate, 2012; Guimarães Nobre et al., 2019; UN, 2016; OCHA, 2021b; Weingartner et al., 2020; Weingartner and Wilkinson, 2019). Early action mechanisms were operationalised during the 2017 Horn of Africa drought, where an averted food security emergency supported international narratives of systemic improvements in drought risk management (Daniels et al., 2018; Dubois et al., 2018; FAO; 2018; FAO, 2019; Warsame et al., 2023). Advocacy for drought anticipatory action is increasing, with case-studies of mobile cash-transfers demonstrating a capability to mitigate the severest impacts among the most vulnerable (Costella et al., 2017; Guimarães Nobre et al., 2019; UN, 2016; Daniels et al., 2018). The UN's Central Emergency Response Fund (CERF) now hosts a dedicated anticipatory action funding function (Pichon, 2019), and EWSs with associated anticipatory actions have become the state-of-the-art for drought management.

The Horn of Africa's 2021 – 2023 drought, however, has exposed a continued, extreme fragility of water, food and social support systems in the region. Somalia recorded an estimated 43,000 excess deaths due to drought in 2022, with 1 million excess internal displacements and 23% of

its population becoming acutely water insecure (Figure 2.1a; FEWS NET, 2020; OCHA, 2021a; OCHA, 2023a; OCHA, 2023b; UNHCR, 2021; UNHCR, 2022; IPC, 2022; UN, 2023; WHO, 2023b). Anticipatory actions did not receive significant financing relative to the scale of humanitarian impacts (Farr et al., 2022; Majid, 2022). Finance instead focussed on a United Nations (UN) coordinated humanitarian response, for which the funding for Water, Sanitation, Agriculture and Hygiene (WASH) assistance remained below 40% fulfilled throughout the drought (OCHA, 2023b; Ikeda, 2021). WASH is frequently underfunded in drought finance, with only 5% of humanitarian response financing in Somalia allocated to the WASH sector compared with 43% for the food security sector (Mourad, 2023; Ikeda, 2021). Furthermore, finance committed to drought mitigation, preparedness and anticipatory action through WASH interventions is scarce, with WASH and Water Resource Management (WRM) activities mostly dependent on inflexible, long-term funding allocations (Kellett and Caravani, 2013; Ikeda, 2021).

3.2.2 Horn of Africa 2021 – 2023: The Genesis of a Drought Crisis

In the Horn of Africa, water shortages during droughts initiate cascading secondary impacts that drive food insecurity risk (Figure 3.1a). Shortages first affect surface water sources and shallow aquifers, transferring abstraction demand to low-resilience urban or deep-aquifer boreholes, which then have an increased risk of mechanical failure, low yields or complete water depletion (Kebede et al., 2017; MacAllister et al., 2022; Foster et al., 2018). Water supply failures cause food shortages through losses of livestock and reduced crop yields (Farr et al., 2022; Warsame et al., 2022), whilst displacing populations towards migration centres when water points fail (Lindley, 2014). Growing demands on remaining infrastructure and resources increase water prices, food prices, disease and civil insecurity risk, which further pressurise local water and food security (Funk, 2020; Lin et al., 2022; Postel, 2017; Wilhite et al., 2007).

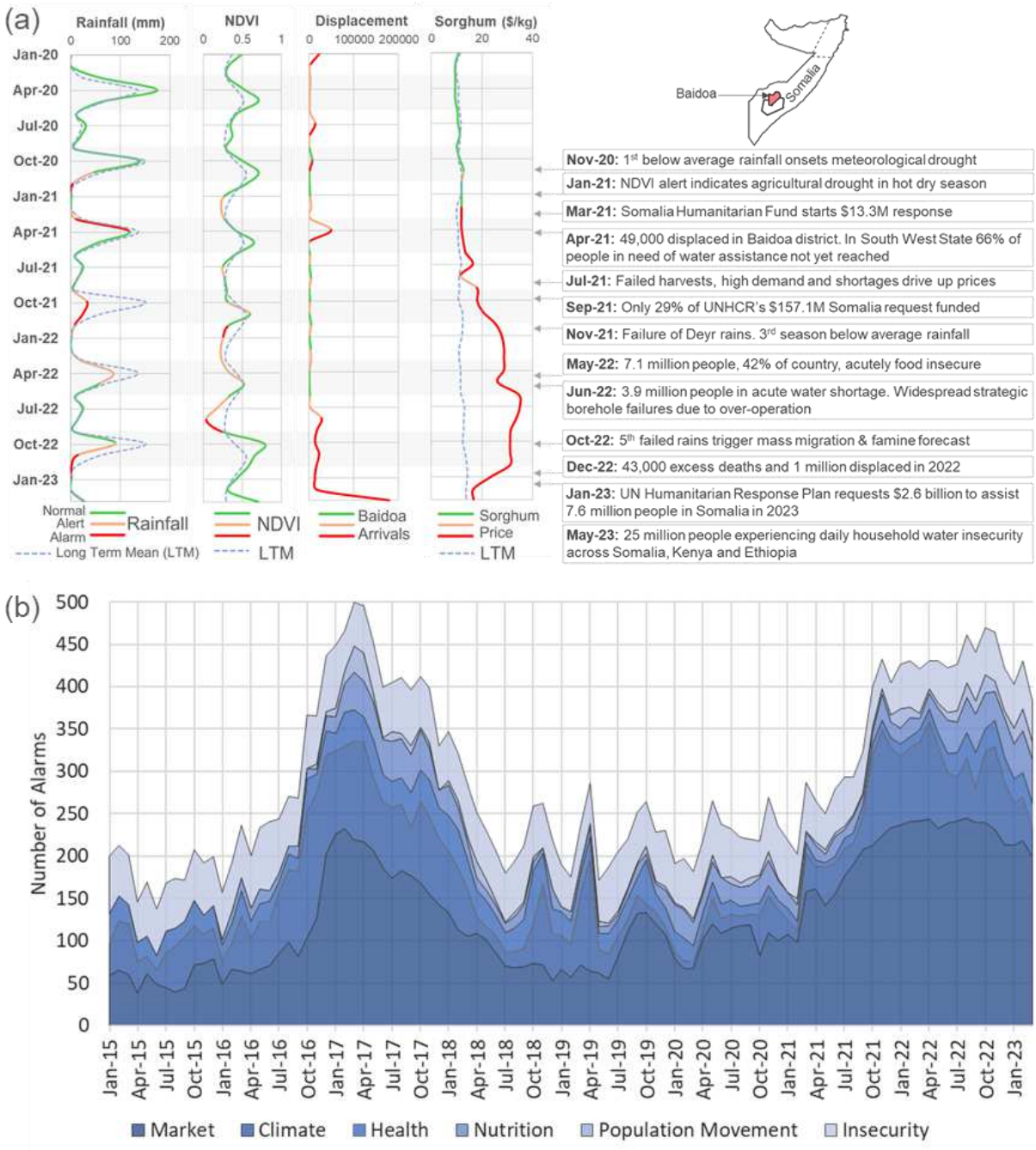


Figure 3.1. (a) Cascading impacts of drought in Somalia from 2020 – 2023. Indicators from the UN Food Security Nutrition and Analysis Unit's (FSNAU) early warning dashboard for Baidoa District are plotted (FSNAU, 2023a). The colour of each line shows the 'normal', 'alert' or 'alarm' status of that indicator on the dashboard during that month (status criteria are explained in Supporting Information; Chapter 3.6.1). A timeline of key events in Baidoa and Somalia is documented from grey literature (FEWS NET, 2020; OCHA, 2021a; OCHA, 2023a; OCHA, 2023b; UNHCR, 2021; UNHCR, 2022; IPC, 2022; UN, 2023; WHO, 2023b). NDVI = Normalised Different Vegetation Index. (b) The number of food security indicators above FSNAU's 'alarm' threshold across Somalia's 74 administrative districts (FSNAU, 2023b).

3.2.3 Droughts and Food Insecurity

Drought is a primary driver of food insecurity crises in Somalia (Krishnamurthy et al., 2022). This is most evident in the Food Security Nutrition and Analysis Unit's (FSNAU) data (Figure 3.1b), where the number of indicators in 'alarm' phase across Somalia during the 2017 and 2021-2023 droughts were over double non-drought levels ('alarm' criteria are explained in Supporting Information 2.7.1). A narrower set of indices monitored during the 2011 drought also showed acute increases in market, nutrition, insecurity, health and population movement indicators of food insecurity relative to non-drought levels (FSNAU, 2011).

This driving relationship between drought and food crises extends across Sub-Saharan Africa (Anderson et al., 2021). However, the complex inter-relationships between drought, conflict, and other socio-political processes means drought's contribution to food security disasters is considered by some authors to be fuzzy, uncertain and 'one of many' factors (AghaKouchak et al., 2018; Little, 2013; Maxwell and Fitzpatrick, 2012). These perspectives downplay empirical (Figure 3.1b; FSNAU, 2023a) and published evidence of the strength of drought's correlation with food security change in drought-vulnerable regions such as the Horn of Africa (Anderson et al., 2021; Krishnamurthy et al., 2021; Maystadt and Ecker, 2014; Pape and Wollburg, 2019; FSNAU, 2023a).

The scale of drought's contribution to food insecurity necessitates a disaggregation of its management from regular food security management processes (Young, 2021). To mitigate the later secondary impacts that generate food insecurity, drought requires the explicit management of the drought hazard itself, by prioritising the mitigation of water shortages and water insecurity (Calow et al., 2010; Action Against Hunger, 2023; Young, 2021; Warsame et al., 2023).

3.2.4 Droughts and Water Insecurity

Water security lacks a universal definition, and its scope has expanded over time to accommodate different framings (Cook and Bakker, 2012). However, the term is most often used in the context of water supply for human consumption (Cook and Bakker, 2012; Young, 2021). Its paradigm definition mirrors the concept food security, as it is the product of the same four domains: availability, access, use and stability (Figure 3.2; Slaymaker et al., 2020; Young, 2021). Availability refers to the physical presence of water in reserves; accessibility is the

ability to retrieve the water for consumption; use describes the safety of the water for its desired applications; and stability constitutes the continuity of the three preceding domains (Slaymaker et al., 2020; Young, 2021).

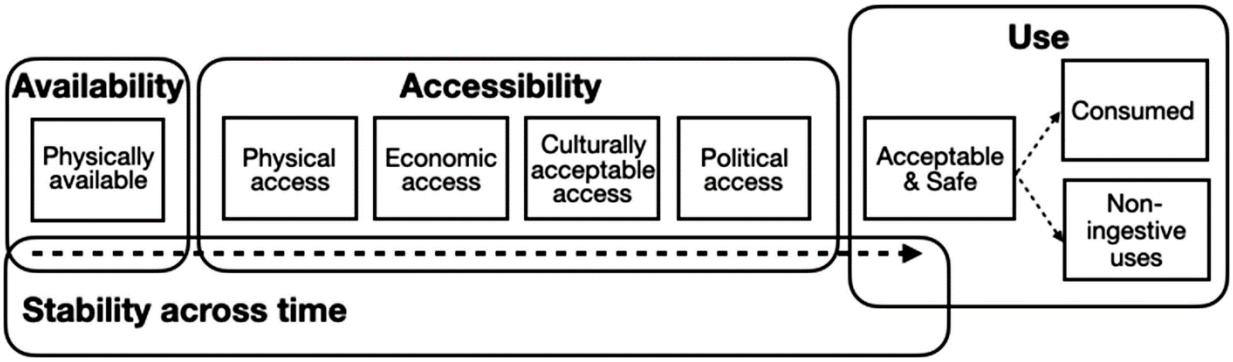


Figure 3.2. The four domains of water security (from Young, 2021). The graphical representation is adapted from a food security review by Jones et al. (2013).

Unlike food security, there is a paucity of water security monitoring data in low- and middle-income countries (Farr et al., 2022; FSNAU, 2023b; Majid et al., 2022). In information systems where water availability information is available, they use low-resolution, satellite-based measurements of rainfall, soil moisture and vegetation health instead of locally collected hydrological measurements such as groundwater levels, river levels and water quality (Mardian, 2022; Wilhite and Svoboda, 2020; Gure, 2021). Socio-economic indicators of water access and use, such as water prices and household surveys, are not routinely collected through EWSs or other humanitarian information platforms (Bedrosian et al., 2021; IMPACT, 2022; Young, 2021; Zaki, 2021). A lack of water monitoring data is recognised as being a significant barrier to water and drought management (UN-Water, 2021b), however, the detailed consequences of this data scarcity for drought management have not been researched.

3.2.5 Study Rationale

It is well-established that WRM stakeholders require better information systems for planning and maintaining drought-resilient supply networks (Kebede et al., 2017; Maxwell et al., 2021; UN-Water, 2021b). However, the design of such monitoring and information systems first requires an assessment of their information needs (Maxwell et al., 2021; Otkin et al., 2022; Young et al., 2021; Wilhite et al., 2007). To this end, I interview 42 expert regional stakeholders during the Horn of Africa 2021 – 2023 drought, with participants ranging in decision-making

level from district water engineers to international financing decision-makers. The interviews and analysis first review perceived barriers to drought management more broadly to contextualise the relative importance of data scarcity issues, then the proceeding analysis assesses stakeholder information needs for improved drought management outcomes. In the ensuing interpretive discussion, I present a conceptual framework visualising the potential role of high-resolution water security data in enabling evidence-based systems of WRM planning and financing during drought. The study concludes with three further discussions. First, I discuss the potential for these data to support a transition in drought and WRM finance towards index-based mechanisms that engage private financers. I then assess the practical considerations of setting-up water security monitoring systems before discussing the further research required to facilitate transitions to these systems. The study's methods including its rationale, semi-structured interview design, sampling, ethical considerations and data presentation are detailed in Chapter 2.

3.3 Results

3.3.1 Drought Management Barriers

Thematic analysis of expert-perceived barriers to drought management organises them in to 6 themes, each analysed in turn in this section (Figure 3.3). To overview, existing monitoring information systems are the modally identified barrier to more effective drought management among experts. At all stakeholder levels, the scarcity of hydrological and regular socio-economic monitoring data is considered a constraint for timely, evidence-based decision making. For Water Resource Managers (WRMs), hydrological monitoring scarcity is a barrier to planning evidence-based, ex-ante interventions that maintain water supply. For financing stakeholders, the scarcity of both hydrological and socio-economic monitoring data means that there is not a sufficiently confident evidence-base to support forecast-based, ex-ante approaches to financing drought-associated actions. Instead, financing stakeholders wait for socio-economic impacts of water shortages to cause significant increases in indicators hosted by EWSs before releasing drought financing at significant scale. Information scarcity, therefore, also underpins the financing barrier to drought management. The capacity barrier is closely tied to financing, as underfunded Water Resource Management (WRM) institutions are constrained by understaffing, a lack of equipment and low technical capacities. Experts also

highlight a range of physical, political and humanitarian access barriers to drought risk management.

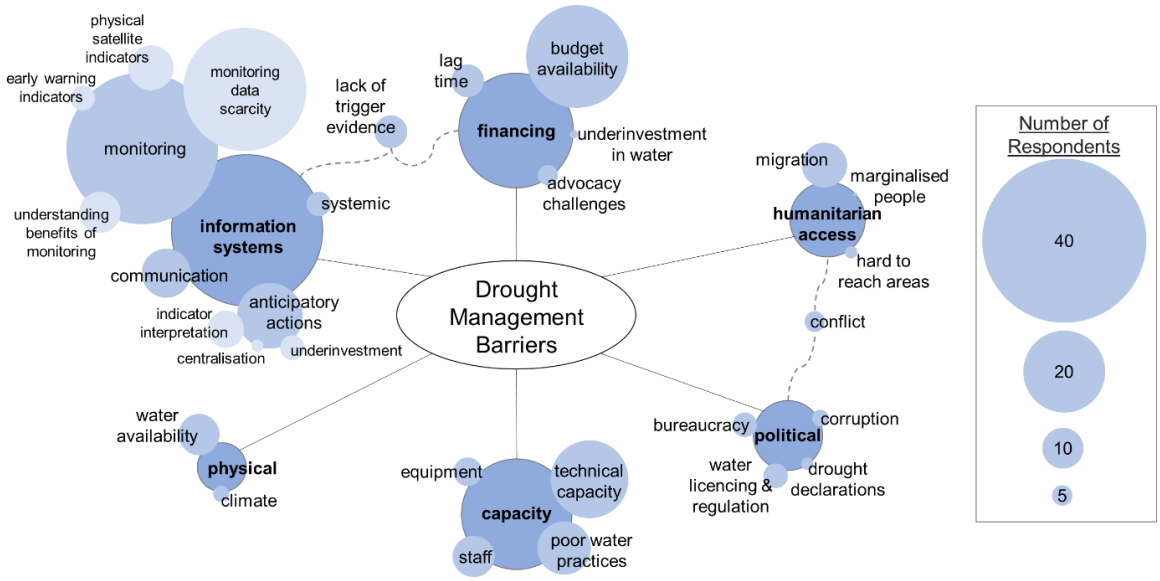


Figure 3.3. Barriers to managing drought impacts perceived by experts during the Horn of Africa 2021 – 2023 drought. Themes and sub-themes are shown, scaled to the number of respondents coded to that category.

3.3.1.1 Information Systems

88% of experts raise existing information systems as a barrier to drought management. They reference monitoring scarcity, unsuitable indicators available on platforms, a lack of water security focus, and poor communication of existing data as prevailing issues.

Leading EWSs in Somalia, including the Famine Early Warning Systems Network (FEWS NET) and the Food Security Nutrition and Analysis Unit (FSNAU), are criticised for spatially and temporally over-aggregating data, creating discrete food security classifications that can over-simplify or incorrectly represent humanitarian needs [NA1, ND3, NE1, PW3, UA1, UA2, UC1, UC2, UW4].

""oh, we've got more red zones than green zones than normal!". I think that those sorts of early warning systems, exactly the kind that the FSNAU dashboard looks like, are kind of a joke."

-UA1

"I realised that the big systems were not granular enough to tell the difference from this place and that place; they weren't coming in at the right time. I couldn't like dig-in and know whether to really trust that data, or that analysis."

-UA2

One expert colloquially describes summary maps produced by these systems as a "curse of the red blobs" [PW1] that have made a humanitarian system "enamoured with food security" [A1], unwilling to fund significant drought-associated actions until real-time food security turns red on district-wide scales on Integrated Phase Classification (IPC) maps [A1, MN3, NA1, NA2, ND1, UA1, UC2].

"a problem with the current system as it's too broad brush. You know, the indicators will give you an error on a district wide approach, but it won't tell you that this particular community is going to go downhill first or, you know, this is what's going to happen here. And I think that much more localised monitoring, with local triggering of local action is what's really needed."

-PW1

The low frequency of data available on these platforms [NA1, ND1, ND3, UA1, UC1, UC2, UW4] and the opacity of the source information behind discrete classifications [ND2, PW3, UA2, UA1, UC2] mean that there is a further lag time until management interventions can be confidently planned and financed. A lack of timely, granular and confident evidence of humanitarian and operational needs is considered a leading factor behind the financing barrier (Chapter 3.2.1.2) - a lack of evidence for value propositioning drought-mitigating actions constrains the timing and scale of their financing [MD4, ND5, NW1, NW2, NW4, PW4, UA1].

"if we do not have evidence that we can show to donors, how are we going to persuade them to finance special projects to manage the drought?"

-ND5

An acute scarcity of local water security monitoring data on information platforms is a barrier to WASH professionals, WRMs and drought coordinators when conducting population needs analyses. They consider this data to be undervalued and subsequently underfunded [MD4, NW2, NW4, NW5, PW5, UC1, PW1, A1].

"we want to organise ourselves at the National Platform and know how to reach those people before they are displaced, because it is actually cheaper to assist people who are lacking water in their villages than to wait until they migrate. Otherwise, their needs are going to

increase; maybe they now need shelter, they will need food, they need other things. So, we want to try and actually be proactive in that way."

-NW1

The absence of water security data limits WRMs' abilities to plan appropriate early interventions that maintain water access [A3, MD3, MD4, MN1, ND4, NW4, PW5, UC1]. For example, the absence of groundwater level and quality monitoring means water shortages are rarely anticipated before supply failures occur [MD3, ND2, ND3, NF1, NW1, NW3, PW5, UA1, UC2]. In the long-term, this missing data also constrains the identification of productive aquifers for more sustainable borehole siting [MD2, MD3, MD4, MN3, ND2, NDF2, NW2, NW5, UW2]. This contributes to supply failures in poorly designed infrastructure being unmitigated and widespread during droughts, with reactive solutions designed upon reports of failures [GO1, MN3, MD2, A1].

"at the moment, I still feel everything is reactive."

-GO1

"whenever the droughts come, it's a repeat cycle - water trucking, water trucking, water trucking."

-MN3

"the emergency approach is to resort to trucking pretty quickly, which is very expensive and inefficient."

-A1

Although increasingly available, satellite remote sensing datasets are perceived to be too coarse, inaccurate and uncontextualized to be actionable as confident indicators of local water availability to guide WRM decisions [ND2, ND3, ND5, NW4, PW3, UA2, UC1, UW1, UW2].

"we have found many times that NDVI [the Normalised Difference Vegetation Index] can be misleading. There are sometimes increases or decreases in places that do not match what we see when we visit the sites."

-ND2

"I am concerned about the way that it is moving – it feels like more and more funding is going in to satellite data analysis."

-NW1

Of the WRM-relevant data that is collected, existing EWSs do not tailor communication to WRM stakeholder needs and alternative systems for socio-hydrological information sharing are absent or poorly developed [PW3, PW4, MD4, NA1, ND5, NW4]. Indices such as rainfall anomalies, NDVI and water prices are presented in aggregated, coarse and opaque formats on existing information platforms, with few tools for interpretation or analysis [UA1, PW1, UC1, ND2, NA2, NA1, A1] (Haile, 2005).

Higher-level stakeholders within government, development, humanitarian and donor institutions also feel their information needs are not being met during droughts by existing information systems, expressing frustration EWSs' failures to adapt in response to evaluation and feedback [ND3, PW3, UA1, NW1] (Maxwell et al., 2021).

"I'm very unhappy with the FSNAU, as it is right now. I think it's stuck. It's not open to the changes that are needed to bring it up to date."

-PW3

"we haven't seen huge jumps forward in how early warning works in Somalia; we are still very much driven by personalities."

-UA1

The information system barriers experienced by higher-level financing decision-makers link closely to the financing barrier [MD4, ND5, NW1, NW4, PW4, PW5, UA1].

3.3.1.2 Financing

"a no regrets approach has not been happening this year. Somalia is really struggling with funding - the HRP [Humanitarian Response Plan] is currently funded at 3.8% [of the requested amount]."

-NF2

Despite broad awareness that earlier actions generally have improved cost-benefit analyses (CBAs) and returns on investments (ROIs) compared to humanitarian responses, they remain underfunded for droughts [NF2, UC1, ND5, NE2, NF1, NF2, PW1, UC2] (Cha et al., 2018).

"as a coordinator, often we cannot take anticipatory action, not because we are not anticipating. But because we cannot take action. Because anticipating is not rocket science - if two rains fail, and the next one is failing, you have already 100% anticipated. But, just, we cannot raise the money."

-UC1

The paucity of socio-hydrological data and the food security focusses of existing information systems mean that drought financing still depends on perceptible evidence of significant food insecurity for their financing at scale [PW1, UA1, UA2, NA1].

"there's still a prevailing perspective that people want to see the red on the map. They want to see the desperate situation on the ground before they will actually take any action. And this is particularly true in terms of government because they have limited funds set aside for emergency response."

-PW1

"I gave a presentation to the team, like a month after I joined, because the Somalia trigger was insane. I mean, it was just based off, I think, IPC [Integrated Phase Classification of food security] warnings, and the Ethiopia trigger was basically just based off IPC classifications. That is like, not just acting after meteorological drought, but it's acting even after the impact – for early action!

-UA2

The financing of proactive, ex-ante actions focussed on securing water supply are particularly obstructed by the scarcity of water security data [PW3, PW4, PW5, UC1, UC2]. Without these data, cost-benefit analyses (CBAs) of actions cannot be confidently formulated for financing requests [UC2, NF1, NF2, A1, A2, NA1, NA2, ND2, ND3, NE1, NE2, NW1, PW1]. Current and forecasted water security cannot be calculated with confidence, and the extent to which water security will impact food security and broader humanitarian outcomes cannot be locally defined without historic water security data to identify correlations and causalities [NA1, NA2, PW1, UA1, A1, A2] (Wilhite et al., 2007). Therefore, the full benefits of taking water shortage-mitigating actions cannot be quantified for a CBA [PW4, UC2]. Without confident CBAs of projects to attract finance from limited capital pools (Basolo et al., 2009), finance is instead channelled to other regions, countries or humanitarian crises until measurable humanitarian need has sufficiently increased in the drought-affected region [A1, NE2, NF2, UC2, UA1].

"the humanitarian sector in general doesn't like the idea of uncertainty. They need something to be concrete, yet Early Warning Early Action is, inherently, embracing uncertainty in some ways, right?"

-NA1

"I was previously doing a lot of the nitty gritty kind of analysis for early warning. I had a pot of money, and I was trying to decide, do I use my pot of money now? Or do I hold that pot of

money for a more rainy day, so to speak. This put me in a nitty gritty war with FSNAU, essentially trying to triangulate if the things they were saying were right in my areas."

-UA1

The absence of regular water security data collection explains the scarcity of dedicated, pre-positioned financing mechanisms for drought management [ND5, ND1, ND2, NE1, NF1, UC2]. Ex-ante financing systems are index-based, requiring accurate indices with low uncertainties to trigger pay-outs once their values exceed pre-set thresholds (Durand et al., 2016). However, when indices have a high uncertainty, there is a high basis risk for both the financing and receiving parties, where pay-outs can be misrepresentative of needs [NF1, NA1, ND2, ND3, NE2, UA1, UA2]. This high basis risk currently constrains interest in existing parametric insurance and insurance-linked securities for drought, as they are indexed by low-resolution, high-uncertainty satellite-based indices [NF1] (Clarke and Hill, 2013; Durand et al., 2016; Ikeda et al., 2021; Okpara et al., 2017).

The transition of drought finance to ex-ante mechanisms is also inhibited by a global scarcity of evaluated case-studies, where the value of ex-ante actions has been quantified in drought areas, to motivate the routine financing of these actions based on established general principles [UC2, PW3, PW4] (Dasgupta, 2021). The scarcity of high-resolution water security data is responsible for the paucity of evaluated examples, as it is not possible to fully evaluate the impacts of ex-ante drought interventions without these data [UC2, PW3, PW4].

"donors do not give us give us a lot of funding, right? Because anticipatory action, it's very difficult to prove the result. It's not really visible without the right data. But if we have, say, people dying, and we do massive water trucking, it's really catchy, right? Media-wise."

-UC2

Funding lag-times in early drought phases allow unmitigated water shortages, triggering water scarcity, food shortages [A1, NA1, ND2, ND3, ND5, UA1, NF1] and displacements [UA1, PW1, NW1, A1, MN3, ND3, NF1, NW2, PW2]. Humanitarian needs, management costs and resource scarcity also compound following late financing [UW3, NE1, PW3, PW4, PW5, UA1, NA1]. For example, the failure of boreholes increases the costs of supplying emergency water from the functional point sources that remain, risking shortages at strategic sites and internally displaced person (IDP) facilities through the ensuing stages of drought [UW3, NE1].

"the water prices for trucking in Somaliland are now up, in some areas, to 20 – 30 $US/m3. And again, even if we compare it with let's say the UK, the price is still about 2 $US/m3. In Nairobi, around 1 $US/m3.

-UW3

"we have to stock water trucking for 45,000 people in the next couple of days, but as of now I still do not have any source [of money] to continue this very crucial activity. So, we may have to exit prematurely, and that will be serious, you know, particularly for the displaced population."

-NE1

3.3.1.3 Capacity

Low technical, staffing and resource capacities of WRM institutions are a barrier to maintaining drought-resilient water networks. These institutions are underfunded, especially relative to humanitarian programmes, yet they are principally responsible for managing and maintaining clean water supply.

"it's the capacity of organisations to actually use information and be adaptive, etc. that is actually holding this thing back."

-UA1

A shortage of resources, staff and equipment prevent WRMs from taking some desired water-securing actions [MD1, MD4, ND4, ND5, NE1, NW4, UW3, A1, A3, MN2, ND2, NW2, PW3, PW4, UC2, UW2]. Their capacity to design complex water supply solutions is also inhibited by low technical skills, as sustainable, resilient solutions for complex supply systems require a commitment to water monitoring, diagnostic testing, analysis and evidence-based design [A3, GO1, MD1, MD2, MD3, MD4, MD5, MN2, NA1, NA2, ND4, NW1, NW4, PW1, PW3, PW4, UA1, UC2, UW2].

Low capacity limits the reach of WRM institutions, enabling poor water practices to become commonplace among private, community and district engineers [PW3, PW4] (MacAllister et al., 2022; Upton et al., 2017). Without a water authority routinely monitoring or maintaining a significant local presence, unregulated water infrastructure development creates low resilience supply networks that fail quickly under drought conditions when demand increases [MD4, MD5, MN3, ND1, ND4, ND5, NE1, NW1, NW2, PW3, PW4, UW2] (Foster et al., 2018; Kebede et al., 2022).

"these institutions don't have the capacity to regulate or penalise contractors who cut corners."

-PW4

3.3.1.4 Physical

Physical shortages of water are considered a characteristic of the drought hazard rather than a major barrier to its management. In deep boreholes, water supply rarely fails due to the depletion of water availability, but frequently, these boreholes fail due to the transfer of demand from shallow and surface sources onto strained infrastructure [MD1, PW3, PW4, MD4, PW5, A1] (Calow et al., 2010). However, in remote areas with poor aquifers, such as southern and eastern Somaliland, genuine water shortages in accessible, freshwater aquifers are a barrier to siting boreholes with an adequate water availability [MD5, MN3, ND5, ND1, UW3].

3.3.1.5 Humanitarian Access

The most vulnerable communities to drought are often in conflict areas, remote settlements, or those actively migrating. When water and food supplies fail in remote or conflict areas, humanitarian assistance may not be accessible [MD4, ND5, NE1, NF1].

"with migration comes mortality, especially for children."

-NE2

Experts identify the shortage of real-time migration data, and the current difficulty in predicting migration source areas and routes, as a barrier to supporting the vulnerable and displaced [MD4, MN3, ND3, NE1, NE2, NF1, NW1, NW2, PW2, UW1]. They cite a lack of local food and water security data for anticipating migration source areas and routes in advance [NE1, NW2, UW1]. Migration that exceeds clan or tribal boundaries needs more anticipatory mitigation, as it is seen as a cause of flash-escalation in vulnerability and humanitarian needs when migrating communities are subjected to marginalisation or conflict [UA1, A1].

"you don't want your anchor water points to fail. Because when your anchor points fail, you get people migrating outside of their normal clan lands and areas. And that tends to be when really bad things happen."

-UA1

3.3.1.6 Political

Conflict is equally viewed as a political barrier, compromising public services, trade and humanitarian activities that support the drought-affected [NE1, ND5]. Political bureaucracy surrounding early warning interpretation, and when to officially declare drought or famine, is also a short-term bottleneck on the release of funding by governments and humanitarian organisations [GO1, NF2, UA2, MW2, NE2, PW3, UC2] (Maxwell et al., 2023). There can be hesitancy among governments to formally declare emergencies, especially in election years, as it may compromise their public image [NF2, UA2]. This can lead to costly funding delays while humanitarian needs escalate.

> *"some of the grants and resources come available after declaration of drought, and this is kind of common in many other countries also, not only in Somaliland, for example, when the government declares that there is a drought emergency, then some of the international community will start to allocate some funds and resources."*
>
> -UW3

Public image considerations inhibit the financing of longer-term, resilience building or anticipatory solutions, even when a positive return on investment is clear [UW3, NA1, UC2] (Wilkinson et al., 2020). Political myopia can cause a preference for short-term benefits [UW3]. There is also a reluctance to dedicate resources to disaster mitigating actions if it does not earn recognition among voters or colleagues [UC2, UW1, UW3, NA1] (Depoorter, 2006).

3.3.2 Existing Information Systems

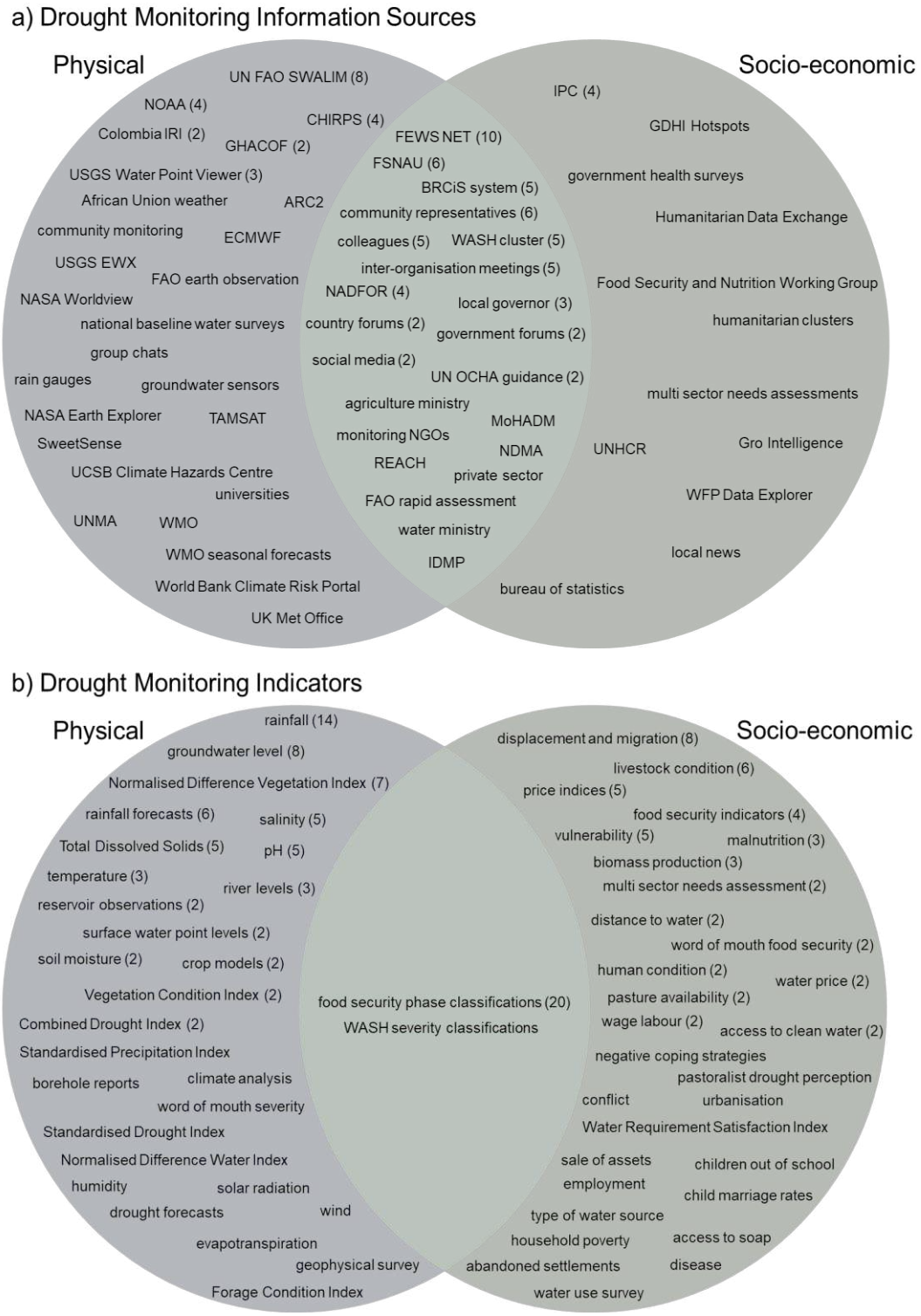


Figure 3.4. (a) Information sources and (b) indicators used by expert respondents to monitor drought. These are thematically categorised as sources of information on physical drought, socio-economic drought, or both. The number of participants using each source or indicator is shown for those that are raised by multiple people. A list of acronyms is provided in Supporting Information 3.7.2.

A large range of information sources are used by the interviewees for both physical and socio-economic monitoring of droughts (Figure 3.4a). FEWS NET, FSNAU and their respective IPC classifications are the most popular, as they aggregate socio-economic and physical indices to form convenient summary maps of food insecurity and humanitarian needs. Actors review these classifications alongside a range of other sources, and discuss these with communities, district authorities, cluster meetings, conferences, working groups, committees and internal colleagues to inform their decision-making [UW1, UA1, UA2, PW1, A1, A2, NF2]. There is notably no popular information source regularly aggregating and summarising the physical information sources for use by less-technical stakeholders. The existing platforms hosting physical drought data are also widely considered to be non-user friendly for non-technical users [MD4, MD5, NA1, NA2, ND5, NW4, PW1, PW3, UA1, UC1] (Maxwell et al., 2021).

The range of drought monitoring indicators used reflects the varying interests of the different stakeholders (Figure 3.4b). Most of the socio-economic indicators are accessed from the FEWS NET and FSNAU platforms (Figure 3.4a), which are primarily used by stakeholders with development and humanitarian interests beyond technical WRM decisions. For the physical indicators, in-situ local data such as groundwater level, river level and water quality are frequently raised by WRMs as useful decision-making tools, despite the collection of these indices being extremely scarce [NF1, NW3, NW5, PW3, PW4, UW2, MN1, MN2].

However, whilst food security has a popular, integrated index through IPC phase classifications, water security and WASH does not have an equivalent popular index, with just one participant mentioning the use of WASH severity classifications [NA2] (Young, 2021). The scarce local collection of hydrological data, as well as relevant socio-economic water security data such as water prices, inhibits the generation of integrated WASH or water security indices with an actionable level of confidence [PW1, NA1, ER2]. Furthermore, the absence of guidance on information platforms on how to link water security data to wider humanitarian impacts causes actors to quantify and interpret this relationship independently, using informal, and often empirical, methods to do so [NA1, ER2, NF1, PW1] (Haile, 2005). Participants subsequently express a need for information systems that support the data's translation to non-technical stakeholders' varying information needs [MD2, NF1, PW4, UC2, UW1, UW2, UW4]. However, some participants are sceptical of the benefits of developing an integrated water security or WASH index, as it may over-simplify issues of water security and repeat the identified limitations of existing IPC classifications for food security [PW3, UA1, UA2].

3.3.3 Water Security Information Needs

Experts focus on two issues when describing their information needs for optimising drought management processes (Questions 4 – 7). First, they explain a need for various improvements in the resolution, accuracy, analysis and communication of the existing monitoring indices available on EWS platforms. Second, over 75% of experts identify a need for high-resolution water security monitoring data to be regularly available. This section presents expert perspectives on this second issue, by analysing water security information needs of stakeholders and the potential impact that regular, high-resolution access to this data can have for drought and water resources management systems. The choice of information needs by participants reflects their prior experience of drought management, WRM and the processes of their financing. Information needs are analysed for WRMs (Chapter 3.2.3.1) and financial decision-making stakeholders (Chapter 3.2.3.2) in turn.

3.3.3.1 Water Resource Managers (WRMs)

Evidence of water security creates a basis for planning WRM actions that prioritise improvements for the least water secure [A3, MD3, MD4, MN1, ND4, NW4, PW5, UC1]. For example, groundwater monitoring networks measuring water availability give a real-time indication of the health of point sources in the supply network, enabling proactive actions to be taken at sites identified to be at high risk of supply failure [MN1, UW3] (Condon et al., 2021; IGRAC, 2020). Groundwater and surface water level data also inform planning focussed on the long-term resilience of water supply. By indicating the relative performance of aquifers, drainage basins and existing water infrastructure, new infrastructure can be developed according to the sustainable capacities of those elements [MD1, MN2, MD2].

"through water monitoring, we can know the water levels in the different basins. And it will be our early warning for making event prepositions; for example, starting water trucking, strategic borehole maintenance and other things before the displacements occur."

-NW1

"we want to be telling people what is happening from the survey and say, "hey, in this region, we have these 10 boreholes that are not working, or in that region that is where they are most affected." There's only one borehole that is functional, it has this much water, it's pumping for this long and we need to fix it before X, Y and Z happens."

-UW1

Indicators of water access and use complete a broader understanding of water security for WRMs, monitored through socio-economic indices. Water prices are considered the best proxy indicator for relative water access, though higher-resolution monitoring is needed for this to become a confident, actionable index [A1, A3, NF1, PW1, UW2]. Water prices are currently collected inconsistently, with significant spatial and temporal gaps on the FSNAU monitoring dashboard [PW1] (FSNAU, 2023a). The current aggregation of these prices to the district level also neglects the spatial volatility of water prices within districts and communities [PW1]. However, water prices are not resource intensive or technically challenging to monitor, and they give a useful indication that a community is in supply deficit relative to demand. Subsequently, water prices also have predictive value for food insecurity, displacement, migration routes and the future failures of overstressed anchor water sources at migration sinks [A1, PW1, UW2].

"price monitoring gives a good indication of availability of water. This then takes into account everything as a proxy indicator – the quantity, quality and accessibility for communities to actually receive or purchase it."

-UW2

"private water trucking can change in price you know, and this can make access to water very difficult for the poorest people that rely on it, especially during droughts."

-A3

Local dynamics and inequalities of water security can be understood through household surveys of water access and use [A1, PW1] (Young, 2021). This data informs the design of tailored, local interventions that prioritise securing water access for the most water insecure [A1]. Household surveys can capture local water prices [A1, PW1, UW2], distance from clean water sources [NF2, PW1], sources of water [NF2, PW1], local threats to water supply [NA2], water bill payments [MD2], livelihoods [NA2], individual WASH vulnerabilities [NA2] and likely migration routes [NW1, UC2] in the event of future water shortages.

Water security evidence improves the scale, accuracy, timing, and quality of the actions that are already taken by WRMs to improve water supply resilience and mitigate drought [A3, MD3, MD4, MN1, ND4, NW4, PW5, UC1]. Borehole drilling and remediation can be completed ahead of drought onsets [ND2, ND3, NW1], based on clear evidence from water security data, instead of being sanctioned according to areas where failures have already occurred [PW3, PW4] (Cha et al., 2018). Advance diagnosis of water insecurity and its causes

through monitoring [MD2, MD1, ND1, NE2, PW1, UA1, PW3, PW4, PW5, MN2] enables rapid action such as engineering support [ND2, UW4, MD3, MD4, ND3], technical advice [ND2, UW4], water purification [MD3], borehole rehabilitation [ND2, ND3, NW1], subsidies [MN3], governance mediation [PW3, PW4] and targeted water trucking [NE1, NF1, UW2]. Cash transfer programmes can also be targeted to the most vulnerable for independent water-securing actions [ND2, NE1, NF1, NF2, PW1] (Costella et al., 2017; Guimarães Nobre et al., 2019; UN, 2016; Daniels et al., 2018).

"shock responsive social protection through cash has been a big improvement in the last 10 years; with vertical and horizontal expansion it has big potential."

-PW1

Beyond its use by WRMs, water security information must also be communicated effectively up the decision-making chain to mobilise the resources of financial decision-makers for WRM actions [UW3].

"our activities often depend on the availability of funds and financial resources from the donors."

-UW3

3.3.3.2 Financial Decision Makers

Experts identify a need for financial decision makers to have clearer evidence of water security to justify financing allocations related to WRM and drought DRM.

"the organisation on the ground would say this is what is needed, and then request funds from this sort of contingency pot."

-NF1

Currently, most drought and WRM financing is sourced from development, government and humanitarian channels, using traditional mechanisms of finance combining internal reserves, external credit and international donations [MN1, UC1, UC2, UW3, NF1] (Chapter 3.2.3.2.1; Ikeda, 2021). Alternative, index-based financing mechanisms are increasingly popular for drought financing through parametric insurance, reinsurance and insurance-linked securities such as catastrophe bonds, which can all accommodate rapid and forecast-based pay-outs [NF1, UA1, ND2] (Chapter 3.2.3.2.2; Clarke and Hill, 2013; Durand et al., 2016; Fava and Vrieling, 2021; Roberts et al., 2017).

3.3.3.2.1 Traditional financing

In traditional financing mechanisms, project finance is reviewed by cost-benefit analysis (CBA) or similar protocols [UC2, NF1, NF2, A1, A2, NA1, NA2, ND2, ND3, NE1, NE2, NW1, PW1]. The forecasted benefits of a project should exceed its costs for financing to be allocated to it [ND5, NF1, NF2, PW1] (Dasgupta, 2021; Pandeya et al., 2016). Furthermore, as demand for finance outstrips supply, the benefit-cost ratio of a financed project should also exceed that of alternative projects synchronously competing for financing [UA1, UA2, NF1, NF2, UC1]. Unfunded projects will subsequently become opportunity costs for the funded project [UA1].

"for the most part, their decision is mostly on more money, less money, right? That's like the main lever of decision making within USAID BHA [United States Agency for International Development Bureau for Humanitarian Assistance]. Do we give more money to Somalia, and less to South Sudan, or whatever. So, they gear their huge early warning systems to be able to, you know, decide on that specific lever."

-UA1

The format of this CBA process varies in formality, degree of quantification and nomenclature between organisations [A1]. In international NGOs, project CBAs can be rigidly quantified and formally reviewed, whereas governmental and intergovernmental committees may deliberate projects more discursively, guided by CBA evidence, but allowing for greater consideration of personal, political and holistic decision-making elements that are less easily quantified [UA1, UA2, NF1, UC1, A1].

"for example, in South Sudan, your country director will be sitting on sort of a board of NGOs, that is talking to donors in the UN, and everyone's kind of sitting in these forums assessing what the needs are. And that kind of triggers [actions in] the humanitarian response architecture as a whole."

-NF1

"in the East Africa region, a lot of that [FSNAU] data was interpreted by the FSNWG (Food Security and Nutrition Working Group), and a lot of that data has been used to inform CERF's (United Nations Central Emergency Response Fund) decisions to release funds in the East African region."

-NF1

Computing project benefits is the most challenging element of financing requests and subsequent allocation decisions [UC2]. Benefits are calculated as the difference between

expected outcomes if no actions are taken and the expected outcomes if a project is financed [UC2, ND5, PW4]. The 'outcomes' considered in that calculation accord to the financing institution's objectives, and they are measured as changes in the monitoring indicators relevant to the organisation's valuation framework [UC2, UW2, NF2]. For example, for a United Nations agency using the Sustainable Development Goals (SDGs) framework, indices for each of the relevant SDG areas can be forecasted and compared between the inaction and action scenarios to compute the project benefit [NA2, NF1] (Dasgupta, 2021; Ikeda et al., 2021). Whereas, for organisations providing contingency credit such as development banks, the project may instead need to demonstrate a positive economic return on investment (ROI) as its primary benefit, with financial savings from the project recoverable and repayable by a loan's maturity date (Ikeda et al., 2021). Benefits and costs are considered in these calculations as Net Present Values (NPVs), where the absolute values of benefits realised at later times are reduced in the CBA by a social discount rate to account for the greater value placed on shorter-term benefit realisation (Ikeda et al., 2021; Dasgupta, 2021). Projects are financed when the NPV of a project's benefit-cost ratio is positive and in exceedance of the ratios for alternative projects [ND5, NF1, NF2, PW1].

"I think it's quite clear that our monitoring information is not up to standard at the moment, and this means that there is no shift in the ability to finance interventions."

-ND5

Currently, the computation of benefits for water-focussed projects is constrained by the scarcity of local water security data [PW1] (Chapter 3.2.1.2). Without consistently monitoring water security indicators, it is difficult to identify current trends in water security or forecast these and their associated humanitarian impacts ahead of time [UC1, UC2, NF1, NF2]. Generally, there is insufficient evidence to forecast and compare outcomes between scenarios of action and inaction based on water security data alone [UA1, UA2, NA1]. Furthermore, these benefits cannot be easily estimated through comparable real-world case studies, as there are few global examples where the benefits of proactive water-supply projects have been evaluated throughout their lifetime [UC2, PW3, PW4]. As a result, benefit-cost ratios of water-focussed projects are difficult to compute at a sufficient confidence level for their financing [UC2, ND5, PW4] (Basolo et al., 2009).

"thanks to the new boreholes, they're saving a lot of lives now. But still, I think enough credit was not given to this anticipatory action as the UN is not mobilising a new round of funding."

-UC2

"it currently needs to already be in emergency to justify triggering the funds and to withdraw them from other places."

-NF1

Experts identify a potential for dense networks of water security data to address this uncertainty bottleneck [A2, MN1, NA1, ND2, ND3, NF1, PW4, UA1, UW1, PW3]. However, to engage higher-level financing stakeholders, water security's relationships with broader development, WASH, food security and humanitarian outcomes must also be explicitly defined for the local context [A2, MN2, NA1, NE2, NF1, PW5, UA2, UC1, UC2, UW1] (Ringler et al., 2018). This step is essential, given the broader scope of most traditional financing stakeholders' valuation frameworks (Wilhite et al., 2007; Dasgupta, 2021; Pandeya et al., 2016; Ringler et al., 2018). These relationships can be drawn simply through empirical comparison, by comparing water security indices during previous drought years with food security indicators during the same time periods [NA1, NE1, NE2, NF1, PW1, UA2, UC1]. Or, to avoid making assumptions or misinterpretations of causality between indicators, more detailed analyses can better establish the nature and strength of relationships through process-based models that are calibrated, sensitivity-tested and validated by historic water and food security data [UA1, UA2, NA1, PW4, PW3].

"historical analysis is also going to be good for forecasting. Like, if the groundwater level is below historical average, and you know the impacts were bad at that certain level in the past, it becomes useful for us."

-NF1

By pre-defining these relationships for local contexts and livelihoods [NA1], forecasted deteriorations in water security can be used to rapidly forecast its subsequent local impacts on food security, the economy, and humanitarian needs [ND3, NA1, NF1, UC1, UC2, NA1] (Maystadt and Ecker, 2014; Pape and Wollburg, 2019; Ngcamu and Chari, 2020; Ringler et al., 2018). Then, where confident forecasts identify a sufficient benefit-cost ratio for early, water-securing actions, traditional financing sources can finance proactive projects aimed at water insecurity mitigation [NF1, PW3, PW4, NF2, PW1] (Pape and Wollburg, 2019). Through

well-defined relationships, water security data can also be used as a predictor for designing and financing appropriate anticipatory actions that mitigate food insecurity and other humanitarian needs [NF1, NF2, UA1, UA2, NA1]. Some anticipatory action projects use hydrological data already, but these are limited to lower-resolution satellite-based indices of rainfall, soil moisture and vegetation indices [A1, ND2, ND3, ND5, NE2, NW4, PW3, UA2, UC1, UW1, UW2, NF1] (Brown et al., 2014; Guimarães Nobre et al., 2019; Wilkinson et al., 2018; Weingartner et al., 2020). Anticipation of water shortage-induced food insecurity enables its mitigation through cash transfers, provision of livestock fodder, short-term supplemental crop irrigation and other tailored actions.

Over time, as more anticipatory, water-centric projects are financed and evaluated through water security, food security and economic monitoring networks, the improved understanding of their benefits for other sectors of development is likely to attract greater funding towards WRM to improve drought impact mitigation [NA1, UA1, UA2, UC2, PW3, PW4].

"to promote more anticipatory action, quantify the impact. If we could say that our current style of response is 10 times costlier than the prevention, this number is quite powerful… and then also, we need to look at how we could showcase good examples and quantify the impact after the project is operated to encourage more anticipatory action in the future."

-UC2

3.3.3.2.2 Index-based Financing

The expansion of index-based financing becomes more viable with improvements in water and food security monitoring [NF1, UA1, UA2]. For example, agricultural parametric insurance coverage has increased with improvements in the accuracy and resolution of satellite-based rainfall and NDVI measurements, triggering pay-outs based on threshold-exceeding NDVI values [NF1, UA1, ND2] (Clarke and Hill, 2013; Durand et al., 2016; Fava and Vrieling, 2021; Roberts et al., 2017). Index-based financing is favoured for its simplicity, quick pay-outs and ability to make forecast-based, ex-ante payments to both smallholders and national-scale stakeholders [UA1, ND2] (Durand et al., 2016; Janzen and Carter, 2019; Noritomo and Takahashi, 2020; Roberts et al., 2017). For humanitarian emergency response, index-based insurance and reinsurance have already become an important financial risk transferring tool for governments and humanitarian stakeholders for high impact, low probability events (Ikeda, 2021, Clarke and Hill, 2013; Durand et al., 2016; Okpara et al., 2017).

However, hydrologically indexed policies by private investors, insurers or elsewhere are yet to scale due to high basis risks faced by both insurers and policyholders [NF1, UA1] (Chapter 3.2.1.2). Dense local networks of water security data have potential for supporting multi-index, precise parametric policies for drought [PW1, NF1, ND2]. Local data can reduce basis risks and improve the viability of smaller profit-margin, smallholder insurance for local water supply networks and agricultural assets. Lowered basis risk also increases the viability of national-scale financing through index-based policies (Ikeda, 2021), where the finance of larger-scale anticipatory drought interventions targeting both water and food security are triggered by higher-confidence, early signals of water insecurity [NF1, PW1].

3.4 Discussion

3.4.1 The Role of Water Security Data for Anticipatory Action

The results suggest that water security data, with analysis of its causal relationships with broader humanitarian impacts, can support the early financing of drought impact-mitigating actions at a greater scale by providing a confident, predictive evidence-base of water and food insecurity. These findings are presented in an interpretive conceptual framework, visualising the flow of water security data in fulfilling both WRMs and financing decision-makers' information needs for planning and financing early actions (Figure 3.5). In the framework, WRMs can use raw or analysed water availability, access and use indices to support a more skilful planning of complex WRM solutions such as borehole rehabilitation, cash transfers and the preparation of surge water supply (Chapter 3.2.3.1). The water security data is then processed according to the financing criteria of different institutions to provide them with a more confident cost-benefit basis for financing WRM projects ex-ante.

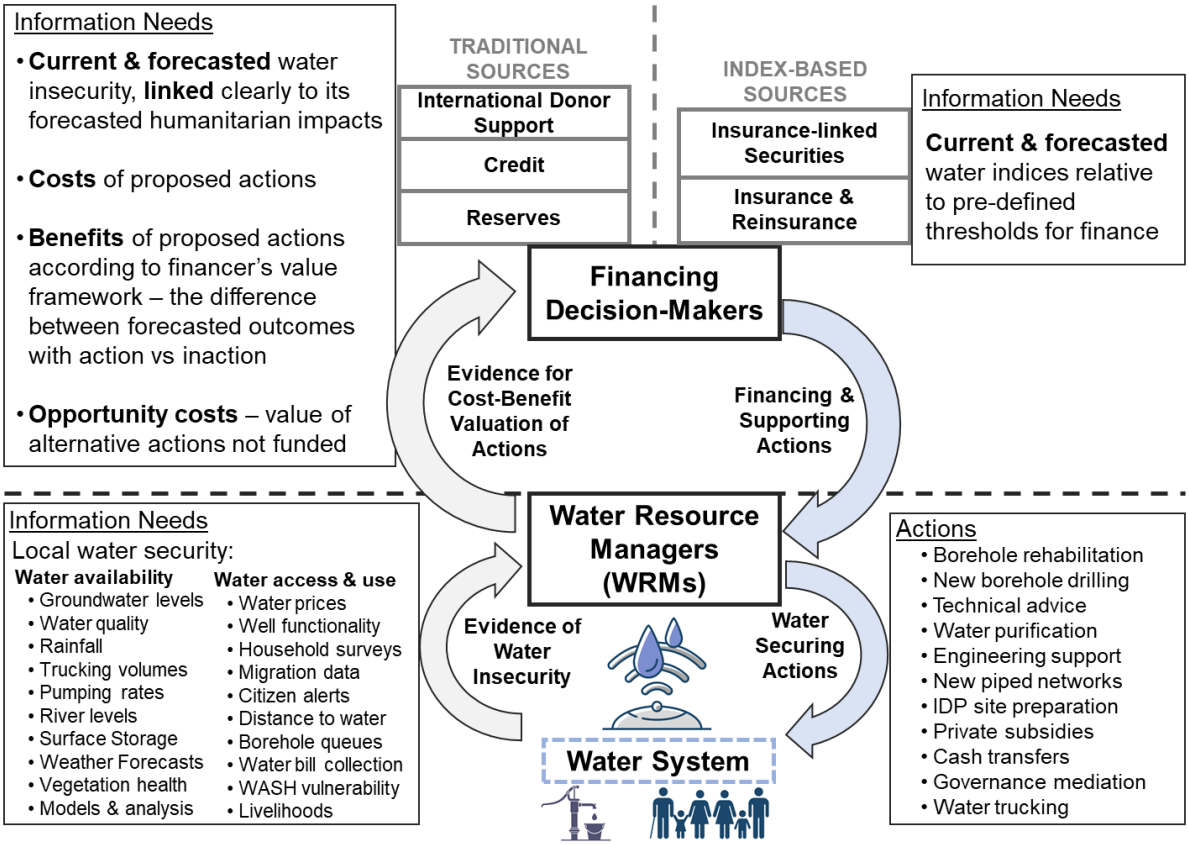


Figure 3.5. An interpretive conceptual framework for water security-centred decision-making, where information needs are met for the rapid approval of proactive, evidence-based actions focussed on water security. Water Resource Managers (WRMs) are the primary users of water security data for planning direct actions that manage water supply systems. Financial decision makers from traditional sources require evidence to justify financing decisions on a cost-benefit basis, and they have a decision-making frame that considers broader development and humanitarian objectives as well as alternative project proposals. Index-based finance sources trigger financial pay-outs once selected indices exceed pre-determined thresholds. The actions and information needs shown are all codes recorded during thematic analysis.

3.4.2 Shifting Towards Index-Based Mechanisms of Drought Finance

Index-based mechanisms that trigger pre-designed actions from pre-positioned financing are faster than traditional finance mechanisms, meaning that earlier and smaller financing requests can be fulfilled at shorter time intervals if these mechanisms can be enabled by local water security data collection (Chapter 3.2.3.2.2; Durand et al., 2016; Roberts et al., 2017; UN, 2016). The availability of higher-resolution local data can also improve the spatiotemporal precision of individual financing requests, facilitating downscaled requests that are more targeted to specific needs. Smaller financing requests can be fulfilled at shorter lag-times, and the targeted

nature of actions improves the efficiency of investments. These effects are visually conceptualised in Figure 3.6, where the cumulative financing needs and actual costs of drought management financing are compared between upscaled, water security indexed financing and the current financing paradigm. Through anticipatory, index-based financing, the overall cost of drought management can be reduced by meeting financing requests at shorter lag times and mitigating further cascading increases in humanitarian needs (Figure 3.6; Roberts et al., 2017; Cabot Venton, 2018; Cabot Venton et al., 2013; Costella et al., 2017; UNICEF, 2015; Clarke and Vargas Hill, 2013; Hallegate, 2012, Guimarães Nobre et al., 2019; UN, 2016; OCHA, 2021b; Weingartner et al., 2020; Weingartner and Wilkinson, 2019).

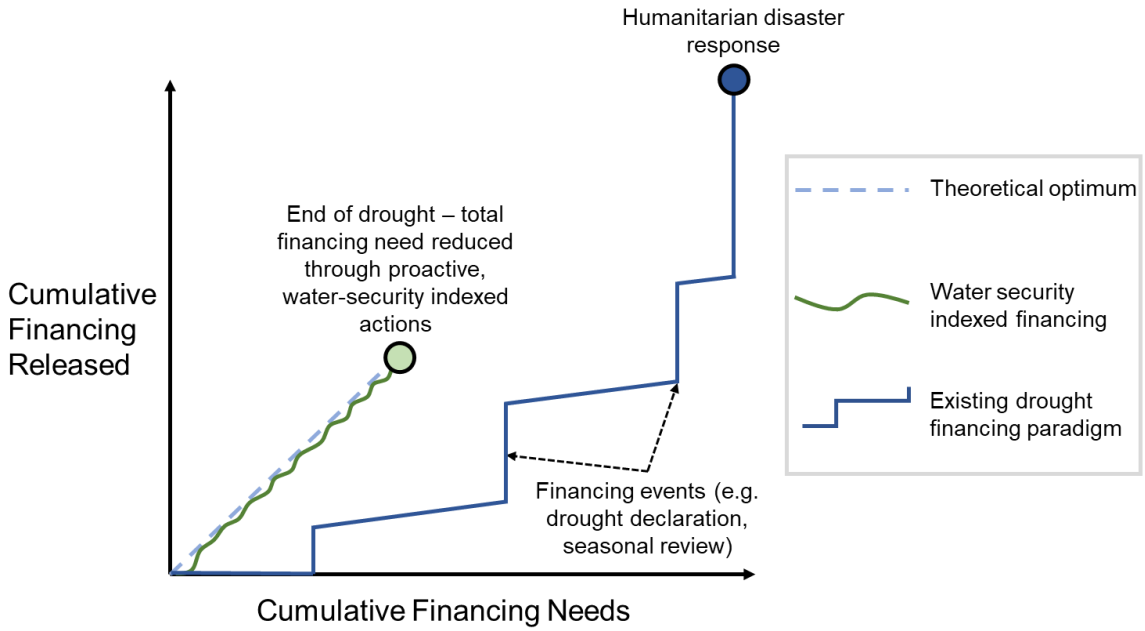


Figure 3.6. Conceptual model of financing needs satisfaction, comparing drought financing indexed by local water security data with traditional financing methods guided by existing EWSs.

Localised water security-indices can shift financing processes away from a dependence on discretised classification maps to enable more localised financing of specific projects. This concept stands in contrast to a recently developed WASH Severity Classification (WSC) solution (Bedrosian et al., 2021; IMPACT, 2022; Zaki, 2021). The WSC, after recognising the need for WASH data to become more actionable by non-technical stakeholders, has been setup to mirror existing IPC food security classifications, creating its own discretised 5-stage

classification to influence the gearing of finance allocations. The WSC has value in drawing a more holistic evidence-base beyond food security to existing traditional humanitarian financing mechanisms. However, its aggregated nature, its lack of local hydrological data inclusion, and its broader, diluted focus on WASH as a broader concept does not fulfil the information need for local water security monitoring to guide the planning and financing of locally specific actions.

Pre-positioned financing and contingency funds need to be in place to dynamically fulfil index-based financing requests at short lead-times (UN, 2016; Weingartner et al., 2020). However, these funds for anticipatory action remain scarce (Weingartner et al., 2020). To motivate financing stakeholders to develop water security-centred, index-based approaches funded by pre-positioned finance, more evaluative case studies are needed, where CBAs and ROIs following ex-ante financing projects triggered by water security data are calculated (Clarke and Dercon, 2016; UN, 2016; Weingartner et al., 2020). This will better elucidate the value of these interventions to high-level policy and financing stakeholders for developing new systems (Pandeya et al., 2016). Clear, positive ROIs and demonstrable scalability can motivate donor organisations, governments and private stakeholders to invest early in pre-positioned funds, if they can expect expenditures to be repaid through savings made from reduced humanitarian finance appeals in the future (UN, 2016). As these proactive management systems begin implementation, it is important for their performance to be continually evaluated and publicly communicated to ensure that implementing actors receive public recognition for anticipatory interventions where the benefits may not be immediately apparent (Wilkinson et al., 2020; Depoorter, 2006). Clear quantification of good, proactive governance, well-communicated, creates greater long-term political value than emergency responses, and it can prompt other governments and international organisations to replicate such systems.

An improved understanding of water-securing interventions' value, through evaluated case studies, will also improve the investment-case for WRM projects in areas where water-security data remains scarce, such as conflict zones, hard-to-reach areas and communities with monitoring implementation challenges, with investments based on principles established from comparable context case studies (Garrick et al., 2017).

3.4.3 Implementing Water Security Monitoring

Creating and maintaining high-resolution, regularly updated databases of water security requires long-term investments in monitoring. Given the data's value to wider humanitarian and development sectors, WRMs need financial support from these sectors to setup monitoring systems and develop institutional capacities capable of maintaining and using them.

Monitoring water access and use requires simple survey methods, like those regularly performed by governments and humanitarian organisations for food security (Young, 2021). However, the hydrological monitoring of water availability is a significant challenge for WRMs (Buytaert et al., 2014). For instance, groundwater is the most-resilient clean water source during droughts, yet the practice of groundwater level and quality monitoring is scarce following a history of underinvestment, implementation challenges and weak WRM capacities for consistently collecting data (Calderwood et al., 2020; Paul et al., 2018). However, monitoring network feasibility has significantly improved through advancements in automatic sensor technologies, telecommunications networks, WRM capacities, and citizen-science methods of monitoring (Buytaert et al., 2016; Calderwood et al., 2020; Ingram and Memon, 2019; Veness et al., 2022). Lower-cost, automatic sensors can now transmit data over global telecommunications networks to information platforms that pre-process the data into usable formats, which can overcome the staffing barriers to data collection, processing and analysis of hydrological data (Calderwood et al., 2020; Dahir et al., 2023). Manual monitoring of hydrological parameters through citizen science and engineering contractors can complement sensor data to maintain a high-density monitoring network (Nath and Kirschke, 2023; Walker et al., 2021). If there are sufficient investments in monitoring networks, and concurrent WRM capacity building for managing those networks, long-term hydrological and water-security monitoring networks will be increasingly technically feasible.

However, the need for concurrent WRM institution capacity building is acute, with further investment needed in their staffing, knowledge and resource capacities to ensure they can take effective actions when early finance is released for water-securing interventions (UNESCO, 2022). The current capacities of many national, district and basin water authorities in the Horn of Africa are poor, primarily due to budget constraints (Alaerts, 2019; Machete and Marques, 2021; Ovink et al., 2023; UNESCO, 2022).

Given the complexity of the actor-network involved in water security monitoring, as well as the complexity of the activities involved in managing monitoring data, the process can be

catalysed by an institution or consortium acting as a "heterogeneous engineer" that takes leadership in organising the actor network (Bosco, 2006; Cressman, 2009; Krige, 2001; Law, 1992; Law et al., 2012). The institution may be district, national or international scale, private, public, governmental or non-governmental, depending on socio-political conditions, and it may also be a proprietor of the data, an external contractor, or a consortium between the two. However, it must have expert knowledge capacity in the complexities of water security monitoring and its integration to users in the actor network. In Somalia, for example, UN FAO SWALIM is well-positioned with prior government integration to fulfil this role, but it will need additional expert capacity (FAO SWALIM, 2023). The heterogeneous engineering institution can support the translation of complex data into actor-relevant, engaging data entities whilst contributing to the network's tactical organisation, capacity building and data governance for its long-term sustainability (Law et al., 2012). The eventual monitoring system developed should be integrated, incorporating data from existing hydrological monitoring programmes already commenced by national water authorities and humanitarian organisations in the Horn of Africa. Information management centres with dedicated staff, embedded in water authority institutions, are needed to ensure long-term monitoring, analysis and communication is maintained (Alaerts, 2019; Machete and Marques, 2021; Ovink et al., 2023; UNESCO, 2022).

3.4.4 Research Needs

There are outstanding research needs that can support the uptake in water security monitoring and the mechanisms associated with taking water security-indexed actions. First, case studies of proactive, drought-mitigating actions are required that evaluate their benefit-cost ratios in different contexts to elucidate their value to financing stakeholders (Chapter 3.3.1; Weingartner et al., 2020).

Studies that explicitly define the relationships between water security and other development, food security and humanitarian indices are also needed to assess the benefits of ex-ante drought and WRM interventions. Furthermore, whilst case-study assessments of these relationships will be a useful contribution (Postel, 2017; Wilhite et al., 2007), the context-specific nature of these relationships in practice means that standard methodological frameworks also need to be developed to guide local assessments. The validation of the relationships between water security and broader development sectors, through real-world case studies, can attract financing

to WRM from other sectors to mitigate issues that have been demonstrably linked to water insecurity (Garrick et al., 2017).

To support investment in the collection of monitoring data itself, the full value of their collection also requires evaluation (Garrick et al., 2017). However, beyond value, the challenges of collecting and integrating these data also require more explicit assessment (Chapter 6). Then, best practice frameworks can be developed to guide monitoring programmes throughout the stages of design, collection, processing, analysis, communication, interpretation, integration, decision-making, sustainable governance and evaluation. Once monitoring networks are implemented, regular evaluations can update methods and best practices to optimise monitoring systems' value.

Organisations responsible for new monitoring systems can integrate learnings from evaluations of existing EWSs (Maxwell et al., 2021). In fact, the popular uptake of water security data by drought stakeholders will likely require integration with existing EWS platforms, as these have become an industry "gold standard" [UA1] and a focal point for monitoring, early warning and needs assessment (FEWS NET, 2023; FSNAU, 2023a). However, given the security sensitivity of hydrological data, research is needed into the ethics, governance and appropriate data privacy agreements for public data sharing before these networks expand and are shared publicly (WMO, 2022). To optimise engagement by non-technical end-users, water security data will require effective marketing that highlights its value and applications beyond its direct, technical use by WRMs. Research into the communication, marketing and integration of water security data into broader humanitarian and financing systems can inform an approach that achieves greater uptake and value realisation.

3.5 Conclusions

The role of drought as a primary driver of food security crises in the Horn of Africa necessitates management approaches that prioritise the mitigation of water insecurity. However, the underfinancing of drought mitigating, preparatory and anticipatory actions remains a significant barrier to shifting from reactive to proactive management.

The scarcity of high-resolution monitoring data is found to constrain processes of humanitarian financing, as the information required to confidently generate value propositions for proactive

interventions is not available until food insecurity indicators on Early Warning Systems (EWSs) have significantly increased. The scarcity of water security data is especially acute, preventing confident value propositions for projects focussed on mitigating water insecurity. Without confident valuations, traditional financing mechanisms allocate finance elsewhere towards projects with more confident value propositions and more urgent humanitarian needs. Index-based financing mechanisms for actions during drought, such as parametric insurance, are also constrained by water security data scarcity, as low-confidence trigger indices in these ex-ante mechanisms create a high basis risk for both insurers and policyholders.

However, higher-resolution networks of water security data are increasingly technically feasible and have a potential to address the information bottleneck to finance, by providing an evidence-base for more confident cost-benefit analyses (CBAs) of ex-ante water-securing projects. CBA value propositions can use higher-confidence assessments of current and forecasted water insecurity, linked to its forecasted impacts on broader humanitarian and development outcomes, to detail the improvements in outcomes (benefits) if water-securing projects are financed (Basolo et al., 2009; Wilkinson, 2012). Furthermore, once relationships between water security and food security outcomes are well-defined for the local context, high-resolution water security data can provide predictive evidence for locally tailored, ex-ante anticipatory actions that mitigate food insecurity.

Confident assessments of water security and project CBAs, calculated in near real-time, can shift drought and water resource management (WRM) financing towards faster, index-based methods. Pre-planned actions, tailored to the local context, can receive timely finance if sufficiently confident water security indices are available that then exceed pre-defined local thresholds. Higher-resolution monitoring can also downscale and improve the precision of index-based financing requests to further reduce the lag-times of finance allocations.

Evaluated case studies of ex-ante drought interventions, indexed by water security data, are needed to encourage investments in pre-positioned systems of monitoring, financing and action. Positive socio-economic Returns on Investment (ROIs), positive CBAs and clear political value to the public and professional images of the implementors will encourage others to replicate proactive systems (Wilkinson et al., 2020, Depoorter et al., 2006).

By helping to quantify the value of WRM actions, high-resolution water security data can also attract more funding towards building the capacities of WRM institutions, whose low capacities

are a significant barrier to developing drought-resilient water infrastructure (Garrick et al., 2017). Regular hydrological data also creates an evidence-base for WRM planning and governance that improves the quality and cost-efficiency of WRM practices.

Operational water security monitoring networks will require substantial investment to setup and maintain. Regular collection of water prices and household surveys can indicate water access and use, and their collection can be integrated with existing food security surveys to reduce their resource-intensity (FAO, 2023). However, hydrological measurements of water availability are more challenging to upscale, requiring investment, technological expertise and capacity building of implementing organisations to setup, maintain and integrate these data into decision-making processes.

To attract project finance for water security indexed drought projects, evaluated case studies are now required that demonstrate both the value of anticipatory actions and the value of collecting local water security data to index them. If implemented projects can demonstrate positive cost-benefit analyses, returns on investments and positive political value to the implementors, it will encourage further investment into local water security data collection and associated management systems (Wilkinson et al., 2020, Depoorter et al., 2006). By facilitating a transition towards a localised, ex-ante infrastructure of financing for drought in this way, local water security data collection supports one of the main objectives in modern drought management of fundamentally shifting from reactive to proactive approaches.

3.6 Supporting Information

3.6.1 FSNAU Indicators and Alarm Thresholds

Indicator Categories	Early Warning-Early Action (EW-EA) Indicators				PHASED THRESHOLDS		
	INDICATORS	DEFINITION	THRESHOLDS	DATA SOURCE	NORMAL	ALERT	ALARM
1. CLIMATE	Rainfall	% of long-term mean (monthly)	% decrease below average (Based on thresholds)	SWALIM/ USGS	<20% decrease/Any increase	20% – 60% decrease from LTM	> 60% decrease from LTM
	Normalized Difference Vegetation Index (NDVI)	% of long-term mean (monthly)	% decrease below normal NDVI (Based on thresholds)	SWALIM/ USGS	<0.05 decrease/Any increase	Decrease of 0.05 - 0.125 from Standard Deviation (also known as a "Small decrease")	Decrease > 0.125 from Standard Deviation (also known as a "Large decrease")
	Price of water	% increase (monthly) above five year average	% increase above normal level (Based on thresholds)	FSNAU/ FEWS NET	<5% increase/Any decrease	5% - 10% increase in price over LTM	> 10% increase in price over LTM
	Combined Drought Index (CDI)	Combined Drought Index (CDI)	Combined Drought Index (CDI)	SWALIM	> 1.0 (No Drought)	0.8-1.0 (Mild Drought)	<0.8 (Moderate to Extreme Drought)
	River levels/Flooding	Monitoring river level for flooding or high risk levels	River level above critical levels or flooding	SWALIM	< High risk level	>High risk level but < Bank full	> Bank Full
2. MARKET	Maize prices	% increase (monthly) above five year average	% increase above normal level (Based on thresholds)	FSNAU/ FEWSNET	<5% increase/ Any decrease	5% - 10% increase in price over LTM	> 10% increase in price over LTM
	Sorghum prices	% increase (monthly) above five year average	% increase above normal level (Based on thresholds)	FSNAU/ FEWSNET	<5% increase/ Any decrease	5% - 10% increase in price over LTM	> 10% increase in price over LTM
	Rice prices	% decrease (monthly) below five year average	% decrease below normal/average level	FSNAU/ FEWSNET	<5% increase/ Any increase	5% - 10% increase in price over LTM	> 10% increase in price over LTM
	Local goat prices	% decrease (monthly) below five year average	% decrease below normal level (Based on thresholds)	FSNAU/ FEWSNET	<5% decrease/ Any increase	5% - 10% decrease in price over LTM	> 10% decrease in price over LTM
	Wage labor	% decrease (monthly) below five year average	% decrease below normal level (Based on thresholds)	FSNAU/ FEWSNET	<5% decrease/ Any increase	5% - 10% decrease in price over LTM	> 10% decrease in price over LTM
	Terms of trade (wage labor to cereals)	% decrease (monthly) below five year average	Decrease below normal/average level	FSNAU/ FEWSNET	Zero change/Any increase	1kg - 2kg decrease below the LTM	decrease >= 3kg
	Terms of trade (local quality goat to cereals)	% decrease (monthly) below five year average	Decrease below normal/average level	FSNAU/ FEWSNET	<5Kgs decrease/any increase	decrease 6-10kg	decrease > 10kg
	Cost of Minimum Expenditure Basket	% decrease (monthly) below five year average	% decrease below normal/average level	FSNAU/ FEWSNET	<5% increase/ Any increase	5% - 10% increase in price over LTM	> 10% increase in price over LTM
3. HEALTH	AWD/Cholera outbreak	Magnitude of AWD/cholera deaths	AWD/cholera Case Fatality Rates	Ministry of Health/WHO	0	Case Fatality Rate (CFR) ≤1%	CFR>1%
	Polio outbreak	Number of confirmed polio cases	Number of confirmed polio cases	Ministry of Health/WHO	0	0	1
	Measles outbreak	Number of confirmed measles cases	Number of confirmed measles cases	Ministry of Health/WHO	0	1	≥2
	Malaria	Number of confirmed malaria cases	Thresholds not yet established	Ministry of Health/WHO			
4. NUTRITION	New Case Admissions to Feeding and Treatment Centers	Monthly new case admission compared to five-year averages	Monthly new case admission compared to five-year averages	Nutrition Cluster	<25% increase in admissions compared to average	25-50% increase in admissions compared to average	>50% increase in admissions compared to average
5. POPULATION MOVEMENT	Number of displaced people	Arrivals (monthly)	Significant levels of departures (monthly)	UNHCR/PRMN	<1000 departures	1000 - 5000 departures	>5000 departures
		Departures (monthly)	Significant levels of arrivals (monthly)	UNHCR/PRMN	<1000 arrivals	1000 - 5000 arrivals	>5000 arrivals
6. INSECURITY	# of Security Related Incidents and Fatalities	# of Security Incidents	# of Security Incidents	ACLED	No security incidents	Some security related incidents but no fatalities	Some security related incidents leading to some fatalities
		# of Security Related Fatalities	# of Security Related Fatalities	ACLED	No security-related fatalities	Some security related incidents but no fatalities	One (1) ore more security-related fatalities

Figure 3.7. The table (from FSNAU, 2023b) summarises the indicators displayed on the Food Security Nutrition and Analysis Unit's Early Warning-Early Action (EW-EA) Dashboard and the threshold criteria for those indicators to be categorised as being in 'normal', 'alert' or 'alarm' phases.

3.6.2 List of Figure 3.4 Acronyms

UN FAO SWALIM = United Nations Food and Agricultural Organization Somalia Water and Land Information Management unit

NOAA = National Oceanic and Atmospheric Administration

CHIRPS = Climate Hazards Group InfraRed Precipitation with Station data

Colombia IRI = Colombia International Research Institute for Climate and Society

GHACOF = Greater Horn of Africa Climate Outlook Forum

USGS = United States Geological Survey

ARC2 = African Rainfall Climatology Version 2

ECMWF = European Centre for Medium-Range Weather Forecasts

EWX = Early Warning eXplorer

FAO = Food and Agricultural Organization

NASA = National Aeronautics and Space Administration

TAMSAT = Tropical Applications of Meteorology using SATellite and ground-based observations

UCSB = University of California Santa Barbara

UNMA = Uganda National Meteorological Authority

WMO = World Meteorological Organization

FEWS NET = Famine Early Warning Systems NETwork

FSNAU = Food Security Nutrition Analysis Unit

BRCiS = Building Resilient Communities in Somalia

WASH = Water Sanitation and Hygiene

NADFOR = Somaliland National Disaster Preparedness and Food Reserve Authority

OCHA = Office for the Coordination of Humanitarian Affairs

MoHADM = Ministry of Humanitarian Affairs and Disaster Management

NDMA = National Disaster Management Authority

IDMP = Integrated Drought Management Programme (IDMP)

IPC = Integrated Phase Classification

GDHI = Global Dashboard for Hotspot Identification

UNHCR = United Nations High Commissioner for Refugees

WFP = World Food Programme

4 Updating the Drought Management Framework

4.1 Abstract

The slow, creeping nature of droughts makes them unique from other hazards, and their lack of a clear shock fits poorly with existing disaster risk management (DRM) frameworks. Furthermore, conceptual innovations such as ‘anticipatory action’ create an increasingly fuzzy landscape of DRM definitions for drought, which can obfuscate decision-making and management financing. In this study, 42 interviews with expert stakeholders managing the Horn of Africa 2021-2023 drought and a narrative literature review are used to assess whether conceptual paradigms accurately reflect the operational realities and modern objectives of drought management. Expert accounts first demonstrate paradigm representations of ‘hydrological drought’ as following ‘agricultural drought’ to be contentious. For instance, surface and shallow groundwater shortages can precede significant soil moisture and agricultural deficits, especially where abstraction or irrigation is high. Frameworks that embed this paradigm risk steering early actions towards agricultural interventions ahead of hydrological interventions. The interview findings then highlight a grey area in DRM frameworks for describing actions taken between a physical drought’s forecast and the start of humanitarian response. The ‘anticipatory action’ conceptual innovation occupies this critical window, and these actions can substantially reduce future humanitarian needs with positive economic returns on investment. I propose updating the drought management framework to consist of 4 stages: Resilience Building, Anticipatory Action, Response, and Recovery. ’Resilience building’ can replace the overlapping concepts of ‘prevention’, ‘mitigation’ and ‘preparedness’ for drought, whilst promoting continuous, long-term risk reduction through community-centred approaches. Converging these conceptual innovations to the common framework formalises the changing practices and objectives in drought management, which are no longer accurately represented by traditional DRM terminology.

4.2 Introduction

Droughts incur the greatest global costs of any natural hazard (Haile et al., 2020; Hao et al., 2014; UNCCD, 2022) generating vast, long-term networks of primary and secondary impacts that reach every sector of development and affect an estimated 55 million people each year (AghaKouchak et al., 2021; Nicholson, 2014; UNCCD, 2022; WHO, 2023a).

The slow, creeping propagation of drought and its multi-variate impacts on water resources, agriculture, populations and the environment have made its definition subject to decades of debate (Coetzee and Van Niekerk, 2012; Gillette, 1950; Wilhite and Glantz, 1985; Van Loon, 2015; Lloyd-Hughes, 2014; Staupe-Delgado and Rubin, 2022; Wilhite and Pulwarty, 2017). The most common universal definition of drought describes it as a water deficit compared with normal conditions (Sheffield and Wood, 2011; IPCC, 2022; Tallaksen and Van Lanen, 2004). Other academic definitions further digest drought into stages, propagating from meteorological drought (precipitation deficit) to agricultural drought (soil moisture deficit) and eventual hydrological drought (surface or sub-surface hydrological deficit; Odongo et al., 2023; Van Loon, 2015, Wilhite and Glantz, 1985). However, the challenges in applying these terms in practice, and the varying perceptions of their meaning among stakeholders, mean that the simple, universal term ‘drought’ is primarily used in low- and middle-income countries and communications for Disaster Risk Management (DRM; Smakhtin and Schipper, 2008).

DRM implements the Disaster Risk Reduction (DRR) policy objective, and it encapsulates the pre-disaster stages of the disaster management cycle framework (UNDRR, 2015; UNDRR, 2016). A management cycle of mitigation, preparedness, response, and recovery has developed as the paradigm in practice (Baird et al., 1975; Coetzee and Van Niekerk, 2012; Prince, 1920; Sawalha, 2020), though it is updated in the Sendai Framework for DRR to add prevention and rehabilitation at the start and end respectively (Figure 4.1; UNISDR, 2009; UNDRR, 2015; UNDRR, 2016). This 6-stage definition has not significantly displaced the original 4-stage cycle in literature, and a range of similar frameworks continue to be used (Bosher et al., 2021; Sawalha, 2020). However, all disaster frameworks are united by a clear distinction between pre-disaster phases and phases taking place once disaster has onset (Coetzee and Van Niekerk, 2012; Sawalha, 2020).



Figure 4.1. The paradigm disaster management cycle used in DRM including the 6-stages posited by the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015; UNDRR, 2016).

Drought is fundamentally different from other natural hazards, as the physical hazard develops gradually, with nonlinearly increasing impacts as it propagates (Wilhite and Glantz, 1985; Staupe-Delgado and Rubin, 2022; Van Loon, 2015). As such, the hazard does not have a universally recognisable 'shock' event to demarcate the onset of a disaster and discretely separate pre-disaster mitigation and preparedness phases from response and recovery (Staupe-Delgado and Rubin, 2022). Instead, governments and humanitarian organisations set thresholds, beyond which monitored indicators showing significant socio-economic drought impacts trigger the transition of approach to a dedicated drought disaster response (Maxwell et al., 2023). This transition is spatially, temporally and conceptually fuzzy for droughts, as its subjective interpretation varies with stakeholder perspectives and situational contexts (McKone and Deshpande, 2005; Rosch, 1973; Zadeh, 1978). Spatial heterogeneity causes some districts to enter post-disaster onset phases before others, and different stakeholder thresholds for humanitarian response blur the temporal setting of the boundary (Maxwell and Majid, 2016; Maxwell et al., 2023).

Significant financing is available for response and recovery following natural disasters, accounting for an estimated $1.5 billion (12%) of international humanitarian aid each year (Ranger and Clarke, 2018). Whereas pre-disaster DRM actions that mitigate drought impacts, such as the maintenance of water supply systems, agricultural assistance and cash for social protection, are acutely underfunded (Kellett and Caravani, 2013; Ikeda, 2021; Mourad, 2023). Just $9 million/year of international financing was earmarked for pre-disaster DRM activities across the 10 countries most impacted by drought globally between 1993-2013 (Kellett and Caravani, 2013; Ikeda, 2021). The failures of 'mitigation' and 'preparedness' concepts in attracting financing at scale has contributed to new conceptual innovations to address gaps in management processes and their financing (Meadowcroft and Fiorino, 2017; Simion and Kelp, 2020). 'Early action', 'anticipatory action' and 'forecast-based action' are increasingly popular

concepts that aim to emphasise the benefits and cost-efficiency of taking proactive, pre-disaster actions that mitigate later impacts (Hansen et al., 2022; Tozier de la Poterie et al., 2023). Furthermore, 'resilience building' is an increasingly popular term in drought management, used to describe actions that can also be described as prevention, mitigation or preparedness (Hemond and Robert, 2012; Sawalha, 2020; IFRC, 2016).

The expanding DRM lexicon creates redundancy between similar terms, and fuzzy interpretations of their definitions and situational applicability (Kuhlicke et al., 2023; Rosch, 1973; McKone and Deshpande, 2005; Osherson and Smith, 1981). This issue was identified during interviews of 42 expert stakeholders about issues of drought management in the Horn of Africa (Chapter 2), when conceptual barriers were identified during the first round of qualitative thematic coding analysis. Firstly, inconsistencies in stakeholder interpretations of the meaning of the term 'drought' were coded when discussing DRM matters. Secondly, participants used different DRM terminologies to describe the same activities, they were applying DRM terms to situations contrary to their common formal definitions, and they were explicitly discussing their own confusion when applying terms to different practical situations. The second and third rounds of coding were therefore abductively focussed to identify all cases where drought and DRM terms were applied by participants during the full course of the interviews (Chapter 2).

Whilst complimentary and overlapping terminologies can be useful in translation and communication, an unclarity in their definitions and the respective practical activities that they describe can compromise inter-stakeholder coordination on complex drought management activities (Kuhlicke et al. 2023; Meadowcroft and Fiorino, 2017; Simion and Kelp, 2020). A lack of clarity can also disincentivise investment in those activities if the philosophy and the overall direction of coordinated efforts are unclear (Kuhlicke et al., 2023; Sawalha, 2020; Bosher et al., 2021; UN, 2016). This study therefore addresses a need to review common theoretical drought and DRM concepts and assess whether these reflect the realities and objectives of modern drought DRM (Bosher et al., 2021; Dewey, 1925; Kuhlicke et al., 2023; Peirce, 1878; Rosch, 1973; Simion and Kelp, 2020). Therefore, taking a mixed-methods approach, I complete a narrative literature review of drought and DRM terminologies (methods described in Chapter 2.5), and I use both the results of the qualitative coding analysis, groundwater data collected in Somaliland (Chapter 2.6), and findings in the literature to evaluate conceptual issues and the respective suitability of terms for inclusion in modern

drought DRM frameworks. The study is therefore a commentary-style narrative review (Green et al., 2006; Patton, 2015), aiming to clarify conceptual issues associated with existing terms before proposing an updated drought DRM framework that aligns with modern drought DRM practices and objectives. The framework does not intend to innovate new language or meanings. Instead, it aims to clarify, condense and refocus an increasingly diverse and complex landscape of drought and DRM terminologies (Meadowcroft and Fiorino, 2017; Simion and Kelp, 2020). The structure of the chapter is as follows. First, findings from interviews and groundwater monitoring are used to highlight and discuss conceptual issues in defining drought, which evidences a practical need for the simplification of concepts in drought DRM frameworks (Chapter 4.3). Then, interview data and literature are used to evaluate traditional and emerging DRM terminologies and their applications to drought management processes and objectives (Chapter 4.4). In that section, evidence of conceptual issues in applying the 'preparedness' term to drought, as well as the suitability of 'anticipatory action' and 'resilience building' concepts in addressing those issues, justifies a proposed updating of the common DRM framework for droughts. Chapter 4.5 then discusses how to action the framework and the need for higher-resolution water monitoring systems as evidence to support the upscaled planning and financing of 'resilience building' and 'anticipatory action' activities.

4.3 Defining Drought for DRM Frameworks

4.3.1 Paradigm Definitions of Drought

The perception of what a drought is varies between stakeholder backgrounds and management contexts (Lloyd-Hughes, 2014; Smakhtin and Schipper, 2008). The gradual development of drought, its multi-variate nature, and difficulties in monitoring those variables all make it difficult to establish a formal definition (Crausbay et al., 2017; Lloyd-Hughes, 2014; Smakhtin and Schipper, 2008; Staupe-Delgado and Rubin, 2022; Van Loon et al., 2014).

"I mean drought, for most people, drought is like, the animals don't look good."

-UA1

"drought is a natural phenomenon that can't be controlled."

-MD3

"I think that everyone needs to understand what a drought is… with a drought, the root cause of drought is back to back water shortages due to borehole failures."

-ND3

"when we talk about drought, actually, what we're talking about is economic disruption."

-PW2

"it's government drought declarations that will give the mandate for agencies to define the situation as a drought."

-NF2

"drought is a pretty useless word in the Somalia context, because it means, like, 100 different bad things."

-UA1

Gillette (1950) famously first described drought as a 'creeping' phenomenon, in contrast to other natural hazards where the 'shock' event is of a commonly perceived short duration (Haile et al., 2020; Van Loon et al., 2016). Wilhite and Glantz (1985) identified over 150 separate definitions for drought, and the library of well-reasoned definitions has continually expanded since (AghaKouchak et al., 2021; Crausbay et al., 2017; Esfahanian et al., 2016; Lloyd-Hughes, 2014; Van Loon et al., 2016). Given the multi-variate nature of droughts, and their intrinsic coupling within hydrological and agricultural systems to human activity, a universal definition of drought is said to be impractical (Haile et al., 2020; Lloyd-Hughes, 2014). However, a demand for designing common frameworks to analyse the hazard has established paradigm categories.

'Drought' is most commonly defined as a deficit of water compared with normal conditions (Sheffield and Wood, 2011; IPCC, 2022; Tallaksen and Van Lanen, 2004), but it is often represented as a time-propagation between 4 categories of increasing impact intensity (Figure 4.2; Odongo et al., 2023; Van Loon et al., 2015; Wilhite et al., 1985).

Drought onsets as a meteorological drought, characterised by below-average precipitation over a specified period (McKee et al., 1993; Van Loon et al., 2015). Meteorological drought or high temperatures generate agricultural drought, where soil moisture deficits cause reduced crop yields (IPCC, 2022; Wilhite and Glantz, 1985). Van Loon (2015) argues that soil moisture drought is a better objective term for agricultural drought, given the potential broader impacts

of soil moisture deficits (Corti et al., 2009; Van der Molen et al., 2011). In common representations of drought propagation, shortages in runoff, soil moisture and recharge later generate a hydrological drought following weeks-months of lag time, measured by anomalies in surface and sub-surface water stores (Ogondo et al., 2013; Van Loon, 2015; Wilhite and Glatz, 1985). Socio-economic drought develops concurrently to all three phases of drought, increasing nonlinearly in intensity as the physical drought intensifies (Christian et al., 2019; Otkin et al., 2018).

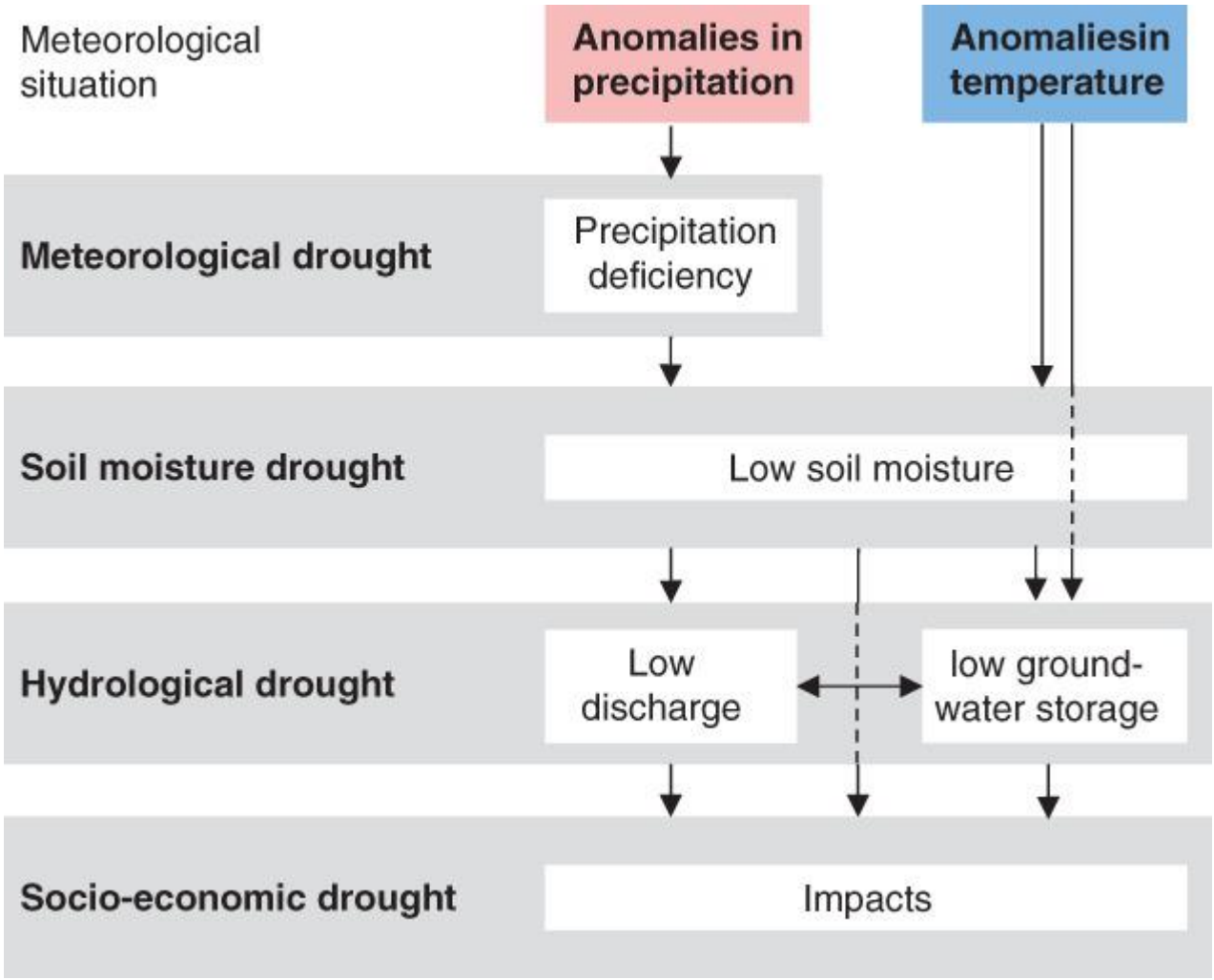


Figure 4.2. The representation of drought propagation by Van Loon (2015), reproduced here, is the paradigm representation of drought categories commonly used in academia, policy and practice (Van Loon, 2015; Peters, 2003; Stahl, 2001; Van Loon, 2013; Ikeda, 2021; IPCC, 2022).

4.3.2 The Challenges of Representing Drought Propagation Phases

Lloyd-Hughes (2014) describes the impracticality of a universal definition for the term 'drought', on the basis that definitions using the terms, 'below normal', 'deficit' or 'anomaly' predicate that normal conditions exist. In practice, at the community scale where humans are exposed to droughts, the strength of human influence on hydrological and agricultural processes is so high that norms are either non-existent due to non-stationarities, or they are difficult to practically quantify (Lloyd-Hughes, 2014).

The same argument applies to drought phase definitions of agricultural, soil moisture, ecological and hydrological drought, which all similarly require normal conditions to be established for their quantification [UA1]. Representative variables for these phases are also difficult to measure locally, and the choice of variables used vary between actors [UA2, PW1, GO1, NA1, NF2, UA2]. Whilst quantification is achieved with more clarity for agricultural drought [UC1, NF2] (Guimarães Nobre et al., 2019), the challenges of quantifying hydrological drought with a representative index means it is rarely attempted in practice (Veness et al., 2022).

Interview accounts and groundwater data analysis exposes a further conceptual issue in the common sequential representations of drought propagation frameworks, which show hydrological drought commencing at a lag time after agricultural drought onset (Figure 4.2). Negative anomalies of surface and groundwater levels can precede significant agricultural drought anomalies, especially where drought-vulnerable water supply depends on rainwater harvesting, waterholes and shallow groundwater wells [ND3, PW1, UA1, UA2, UW1]. For example, during the 2021 – 2023 Horn of Africa drought, a sharp increase in shallow and surface water shortages comprised some of the most severe early impacts in the drought [PW1, UA1, UA2] (Farr et al., 2022; OCHA, 2021a), involuntarily displacing communities before significant food scarcity arose from failed harvests [UA1, NA1, PW1, NE1] (OCHA, 2021a). There are manifold reasons why surface and sub-surface hydrological shortages can precede shortages in soil moisture or agricultural yields:

1. Rainfall events with low peak intensities can maintain a high soil moisture, whilst failing to recharge shallow groundwater aquifers and baseflow-dominated rivers [ND2].
2. Human abstraction of groundwater often intensifies upon the earliest onset of meteorological drought to compensate rainfall shortages, accelerating the anomalous decline of hydrological stores relative to norms [PW1].

3. Irrigation is common and maintains soil moisture throughout a drought, whilst accelerating the anomalous depletion of surface and sub-surface water sources. This activity can inverse the propagation of agricultural to hydrological drought on the local scale [ND5].
4. Deeper groundwater levels can have longer-term negative anomalies that overlap multiple meteorological drought events, due to aquifer recharge processes with multi-year lag times [MN1, PW3, PW4] (MacDonald et al., 2021).
5. Non-stationary human abstraction behaviours can be a significant control of groundwater level changes at water points, causing sub-surface storage quantities to correlate poorly with seasonal rainfall changes or anomalies [PW1, PW3, PW4]. Monitored water levels from an observation borehole (Figure 4.3a) and an abstraction borehole (Figure 4.3b) from Hargeisa and Borama, Somaliland under similar climatic conditions illustrate the impacts of abstraction and varying aquifer properties on groundwater level changes. The observation borehole water level fluctuates in positive correlation with seasonal rainfall quantities, for example, recovering its water level in the March-June wet seasons (Figure 4.3a). Whereas non-stationary abstraction rates in the abstraction borehole cause water level declines during the March-June rainy season (Figure 4.3b), when recovery would otherwise be expected under natural conditions of surface-connected recharge.

Some of the experts interviewed contest the common conception that agricultural drought precedes hydrological drought, arguing that it risks concentrating 'early actions' in drought management on the mitigation of agricultural and food shortages in low- and middle-income countries, instead of the critical early prevention of water shortages and water insecurity [PW3, PW4, MD1, MD2, ND3]. Prioritisation of food security over water security is considered by experts to be a common international failure in the management of droughts, with food security Early Warning Systems (EWSs) still increasingly gearing drought management architecture towards drought emergency responses that are financial indexed by food insecurity indicators [PW1, PW3, PW4, A1, A2, UA1, NW3]. Although the agricultural and hydrological drought terms remain useful for regional-scale remote sensing analyses, conceptual issues warrant their omission from drought management frameworks, especially while local monitoring scarcity inhibits local quantification of their intensities.

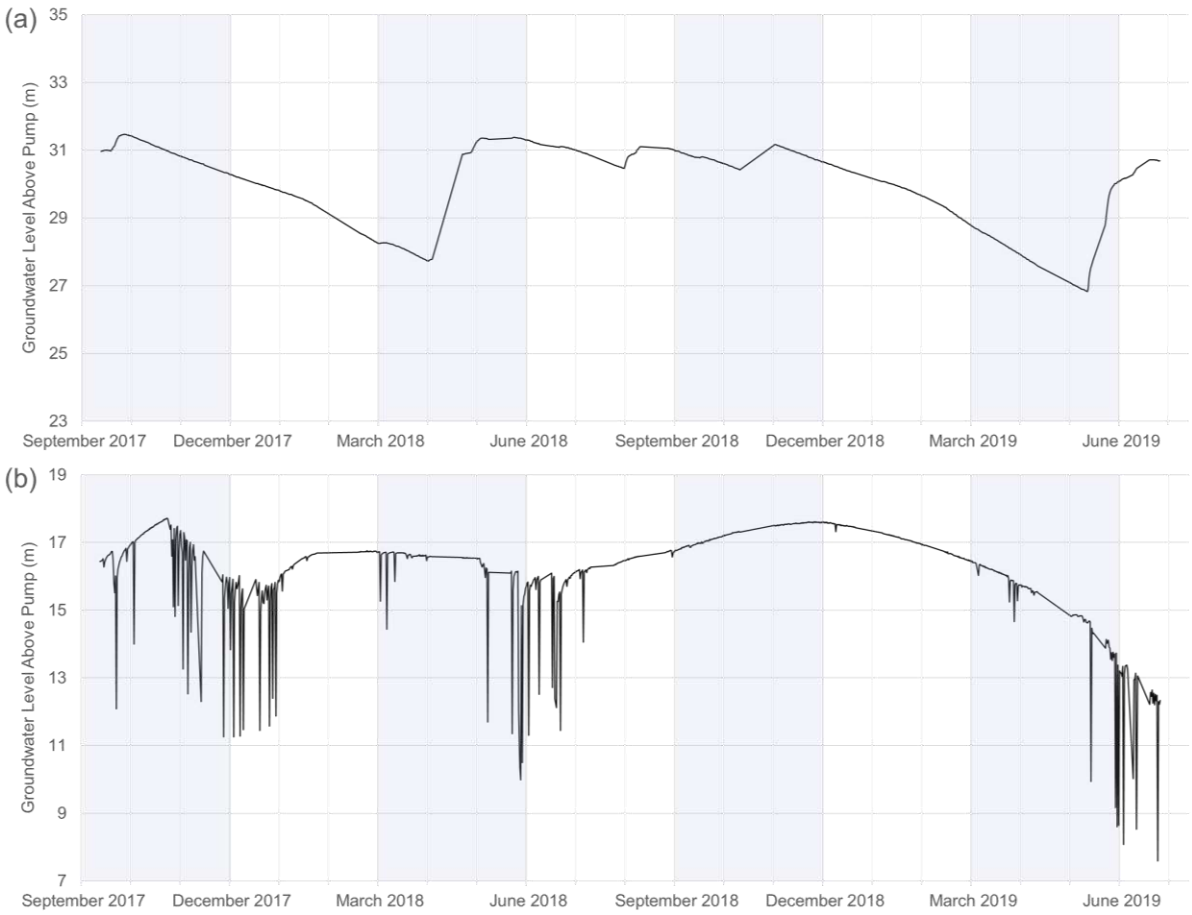


Figure 4.3. (a) Observation borehole water level measured twice daily in Hargeisa, Somaliland. (b) Abstraction borehole water level measured twice daily under similar climatic conditions in Borama, Somaliland. The Gu and Deyr rainy seasons are highlighted blue.

4.3.3 Suitable Drought Definitions for DRM Frameworks

The definition of meteorological drought suffers fewer conceptual issues. Although anthropogenic climate-change induced non-stationarities have a minor impact on accurately establishing rainfall norms, its intensity is measurable relative to long-term climate records using globally available meteorological data, and it is frequently quantified by the Standardised Precipitation Index in practice (SPI; McKee et al., 1993). As precipitation is the sole input to the terrestrial water cycle, it is the primary control of hydrological shortages and therefore the primary measure used to quantify the physical intensity of drought as a collective concept [NA1]. This is reflected by the definition of drought used by UNDRR (Murray et al., 2021) and WMO (2023), who describe drought as "abnormally dry weather characterised by a prolonged deficiency of precipitation below a certain threshold."

The concept of socio-economic drought links water deficit to its impacts, which are caused by reduced water supply relative to demand (Mishra and Singh, 2010; Van Loon, 2015). This shift in the supply-demand equilibrium causes secondary effects on food security, water security, nutrition, health, migration and livelihoods, which are themselves further variables of socio-economic drought intensity. All of these indicators can be affected by other factors such as conflict, global trade, pandemics, locust outbreaks, aid and local governance systems (Maxwell and Majid, 2016), making the quantification of socio-economic drought as an integrated index challenging [UA2, PW3] (Shi et al., 2018).

In absolute terms, socio-economic drought onsets immediately following the onset of meteorological drought, as a rainfall deficit immediately causes some degree of socio-economic impact by affecting crops, ecosystems or rainwater harvesting systems [MD1, MD2, MN1, NW1]. Impacts then continuously increase in intensity as physical drought propagates in various hydrological stores. However, a socio-economic drought is only perceived to have onset by most drought managing stakeholders once the physical drought has caused widespread anomalies in monitored socio-economic indicators [UA1, PW1]. Once the intensity of socio-economic drought exceeds stakeholder-defined thresholds, a transition in management to ex-post response actions occurs [UW1]. The positional setting of thresholds varies between stakeholder groups, locations and livelihood contexts (Wens et al., 2021), but will follow a lag-time of weeks to months [PW1, UC1].

"in these places, there's not really a well-managed understanding of when a shock has occurred."

-UA2

For drought DRM frameworks that are universally comprehensible, applicable and relevant to different stakeholder perspectives and situational contexts, it is pragmatic to use more open, adaptable representations of drought that do not attempt to over-describe a context-dependent phenomenon (MacAskills and Guthrie, 2014; Needham, 1975; Peirce, 1878). Drought DRM stakeholders ultimately want to understand how a physical drought will precipitate impacts in the socio-economic system [PW1, UA1, UA2, NF1, UC1]. If drought risk managers can anticipate physical surface and sub-surface water shortages, then link these to their forecasted socio-economic impacts, interventions can be designed to mitigate socio-economic impacts of below normal water availability through DRM activities [A2, NA1, NE1, NF1, UA1, PW5, UA2, UW1].

Therefore, a conceptual simplification for the purpose of DRM frameworks to a 'physical drought' hazard causing a concurrent 'socio-economic drought' eliminates uncertainties in the use of deterministic drought-phase definitions, and it eliminates the idea that management activities should restrict their focus to managing individual drought phases. Using this simplification in the following sections, 'physical drought' describes the collective deficit of water in the terrestrial hydrological cycle relative to normal conditions. The quantification of its intensity is multi-variable and local context-specific, and the practical objective of measuring its variables is to provide an evidence-base for anticipating socio-economic impacts [UA1, NA1, UA2, PW1]. Simplification to these two concepts ensures drought categorisations in DRM frameworks are relevant and inclusive of all drought management stakeholders, as the open physical and socio-economic drought terms accommodate contrasting management perspectives and objectives (MacAskills and Guthrie, 2014). Reducing the emphasis on over-defined, discretised drought phases also encourages DRM stakeholders need to adapt frameworks to local contexts, as each context has unique physical and socio-economic drought inter-relationships and local drought management needs [UA1].

4.4 Disaster Risk Management Terminology and Drought

"the concepts are very confused – people use them interchangeably without really understanding the difference."

-PW1

The gradual development of the physical drought hazard creates difficulties applying disaster management frameworks in practice [NF2, PW1, UA1, UA2, UC1, UC2, NA1, NA2]. By allocating thematic codes of ex-ante and ex-post actions taken by interviewees during the Horn of Africa 2021 – 2023 drought to the formal definitions of management stages in the Sendai Framework, there is evidence of redundancy between the DRM terms, with actions fitting into multiple categories (Table 4.1). For example, the management of water supply networks through borehole drilling, water trucking and piped network development takes place in all stages of the disaster management cycle in the case of drought, and activities managing social support networks, healthcare systems and food systems overlap the prevention, mitigation and preparedness categories.

Table 4.1. Stages of the Sendai Framework for DRR (UNDRR, 2016), mapped to the actions taken during droughts that can be described by their definition. The drought management actions are collated from interviewees' coded responses to Questions 4 – 7, where they discussed actions taken to manage droughts.

DRM Stage	Definition	Drought Management Actions
Prevention	"Activities and measures to avoid existing and new disaster risks."	• Borehole drilling/rehabilitation • Water governance mediation • Water trucking network setup • Piped water network construction • Desertification rehabilitation projects • Drought-resilient agriculture • WASH (Water, Sanitation and Hygiene) resilience projects
Mitigation	"The lessening or minimizing of the adverse impacts of a hazardous event."	• Borehole drilling/rehabilitation • WASH engineering support • Social support payments • Social support system setup • Water trucking network setup • Food system resilience projects • Healthcare system resilience projects • Piped water network construction • Drought-adaptive farming practices • Drought resilient agriculture • Internally Displaced Person (IDP) site planning • WASH (Water, Sanitation and Hygiene) resilience projects
Preparedness	"The knowledge and capacities developed by governments, response and recovery organizations, communities and individuals to effectively anticipate, respond to and recover from the impacts of likely, imminent or current disasters."	• Borehole drilling/rehabilitation • IDP site construction and expansion • Social system setup • Governance mediation • Water trucking network setup • Emergency food stockpiling • Medical supply stockpiling • Sanitation and hygiene stockpiling • Pre-position financing for rapid emergency response • Piped water network testing • Increase capacity for monitoring humanitarian needs • Advocacy for financing • Setup of monitoring and forecasting systems • Capacity building of Water Resource Managers • Drought-adaptive farming practices • Drought management guidance • WASH resilience projects

Response	"Actions taken directly before, during or immediately after a disaster in order to save lives, reduce health impacts, ensure public safety and meet the basic subsistence needs of the people affected."	• Borehole drilling/rehabilitation • WASH engineering support • IDP site construction • Social support payments • Governance mediation • Water trucking networks expanded • Piped network maintenance • Emergency food provision • Emergency medical care • Humanitarian finance appeal • Increased monitoring of humanitarian needs • Advocacy for financing • Design of drought management plan • Adaptation of farming practices • Emergency WASH support
Recovery	"The restoring or improving of livelihoods and health, as well as economic, physical, social, cultural and environmental assets, systems and activities, of a disaster-affected community or society, aligning with the principles of sustainable development and "build back better", to avoid or reduce future disaster risk."	• Borehole drilling/rehabilitation • WASH engineering support • IDP site operation • IDP relocation • Social support payments • Loss compensation • Governance mediation • Water trucking • Rehabilitation of agricultural and food supply systems • Emergency food provision • Long-term medical care • Adaptation of farming practices
Rehabilitation	"The restoration of basic services and facilities for the functioning of a community or a society affected by a disaster."	• Borehole drilling/rehabilitation • Loss compensation • Governance mediation • Water trucking networks maintained • Rehabilitation of agricultural and food supply systems • Improvement of healthcare systems • Restoration of farming practices • IDP relocation • Community redevelopment • Long-term "build back better" projects

The concept of 'preparedness' is difficult to distinguish from other disaster-related concepts for drought, with a large range and variability in its applications in academic and grey literature (Staupe-Delgado and Kruke, 2018). In its current definition (Table 4.1), the concept encompasses both long-term resilience building actions and shorter-term actions made once an upcoming drought has been forecasted. For example, long-term preparedness actions for drought include WRM capacity building [UW3], WASH engineering support [ND2, ND3, NW1] and the development of monitoring and forecasting systems [ND2, NE2, NF1, NW1 NW2, UW3]. Whereas shorter-term, ex-ante preparedness activities include social support system setup [PW1, UW2, NF1, NF2], stockpiling of supplies [NE1] and the preparatory setup of water trucking supply networks [NE1, NF1, UW2, PW1]. By lumping long-term, sometimes multi-decadal projects with actions taken at weeks-months lag-times before socio-economic drought, the clarity and precision of the preparedness concept is reduced (Kuhlicke et al., 2023; Sawalha, 2020; Bosher et al., 2021; UN, 2016).

The clarity of how to apply the preparedness term reduces further once physical drought has begun, given that 'preparation' and 'preparedness' are words most commonly used to refer to readiness for activities or events taking place in the future (OED, 2023). In the lag period between physical drought onset and the time that socio-economic drought reaches thresholds triggering emergency response, preparedness does not explicitly describe the taking of actions that resolve intensifying drought impacts that are already developing [UW3] (Table 4.1). Instead, preparedness actions are perceived as being in preparation for potential socio-economic impacts developing in the future [UW3] (Staupe-Delgado and Kruke, 2018). A grey area develops in this lag period (Coughlan de Perez et al., 2015), where neither the definitions of preparedness or response explicitly describe the urgent, short-term proactive actions that can mitigate the progradation of socio-economic drought before forecasted impacts develop [NF2, PW1, NA1, NA2] (Figure 4.4).

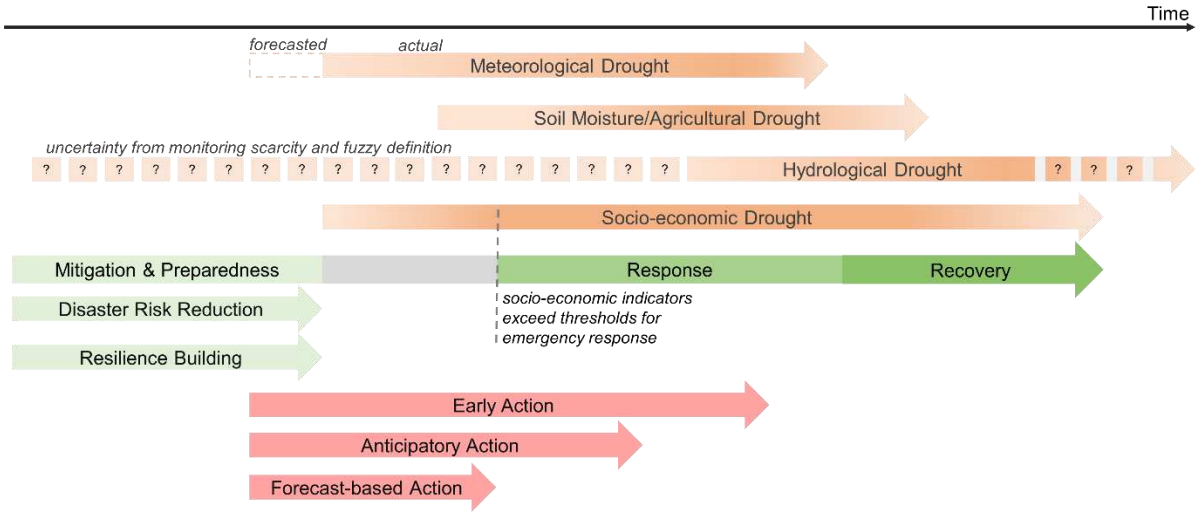


Figure 4.4. Common disaster risk management (DRM) terminologies, with their temporal usage in practice for drought mapped to a paradigm drought propagation timeline. The grey area between mitigation & preparedness and response in the DRM cycle represents a management window between meteorological drought forecasts and response-inducing socio-economic drought, where both terms apply poorly to the unique forecast-based actions taken (Coughlan de Perez et al., 2015; Staupe-Delgado and Kruke, 2018).

4.5 Updating the Common Drought Management Framework

4.5.1 Defining a Place for Anticipatory Action

The conceptual grey area in existing disaster risk terminologies and the acute underfunding of pre-disaster actions has incentivised the adoption of new, conceptually innovative terms to describe actions taken in this grey area [UC2] (Figure 4.4; Coughlan de Perez et al., 2015; Meadowcroft and Fiorino, 2017; Simion and Kelp, 2020; Staupe-Delgado and Kruke, 2018).

Early Warning Systems (EWSs) and associated early actions have expanded following Somalia's 2011 drought and famine, where the need for earlier humanitarian financing was highlighted (Hillbruner and Moloney, 2012; Maxwell and Majid, 2016; Sivakumar et al., 2014). EWSs combine disaster monitoring, forecasting, prediction, risk assessment and communication to enable governments, communities, international organisations and other stakeholders to take timely actions that reduce disaster risks (UNDRR, 2016). In practice, experts describe projects described as early action as often being projects typical of a drought emergency response [PW1, NA1, NA2, UA1] (Majid et al., 2022; Maxwell et al., 2021; Weingartner et al., 2022), where indicators of increasing food insecurity threshold the financing of early actions [NA1, NA2, UA1]. There is flexibility in the interpretation of a 'timely' or

'early' action, and there are clear benefits to DRMs for equivocating their actions as being early and proactive to improve their professional and public images [UW3, PW1, UC2].

"we've had a lot of early response, but we didn't see much early action."

-PW1

"sometimes, what people call anticipatory action, it's actually a response, and not everybody understands the difference. And then they use that word just because they want to have more money, or access to a different source of money."

-UC2

'Anticipatory action' projects are more specifically ex-ante in their definition than early actions, and they are increasingly popular for drought management (Costella et al., 2017; Guimarães Nobre et al., 2019; UN, 2016; Daniels et al., 2018). In academic and grey literature there is a high variance in its description that illustrates a lack of standard definition [PW1].

"a set of actions taken to prevent or mitigate potential disaster impacts before a shock, or before acute impacts are felt."

-IFRC (2020)

The International Federation of Red Cross and Red Crescent Societies' (IFRC) definition is popular (IFRC, 2020), but it fails to explicitly outline that a forecasted or ongoing hazard is a pre-requisite to taking anticipatory action, as other definitions and this study's interviewees infer [PW1, UC1, UC2, NF1, NF2] (CERF, 2021a). If anticipatory action's definition does not necessitate a forecast of upcoming impacts, based on some prior evidence of a forecasted or ongoing hazard, anticipatory action as a concept would not clearly distinguish itself from the preparedness concept (Coughlan de Perez et al., 2015). The IFRC's definition also assumes the presence of a shock, which is less clearly defined during drought.

Therefore, a clearer, more drought inclusive definition for anticipatory action be '*action taken to mitigate the forecasted impacts of a hazard'.* By explicitly requiring a forecast of specific future impacts, the definition clearly differentiates anticipatory actions from preparedness and response definitions (Table 4.1; CERF, 2021a; Coughlan de Perez et al., 2015; Staupe-Delgado and Kruke, 2018). The proposed definition focusses on forecasting impacts, rather than forecasting the hazard, as the hazard and impacts do not neatly coincide in a shock event for droughts, and the mitigation of socio-economic impacts is the objective of the anticipatory actions [PW1, UC2] (Coughlan de Perez et al., 2015).

Anticipatory action has become a focal point for international efforts seeking to transition drought management from reactive to proactive approaches (Meadowcroft and Fiorino, 2017; Wilkinson et al., 2020; FAO, 2021a). International case studies of their implementation show positive economic Returns on Investment (ROIs), where the investment in ex-ante interventions reduces the later economic cost of response through mitigated humanitarian needs [NF1, NF2, UC1] (CERF, 2021b; FAO, 2021a; Wilkinson et al., 2020; Guimarães Nobre et al., 2019). Beyond the economic savings made by DRMs, anticipatory actions hold further value to the individuals assisted through socio-economic benefits and avoided losses [PW1, UC1, NF1] (Weingartner et al., 2020). The United Nations Food and Agricultural Organization's (FAO) international anticipatory action projects estimate US$7 of benefits and avoided losses among targeted farmers for every US$1 spent in their anticipatory action programmes since 2017, without including the less quantifiable benefits made to well-being and long-term disaster resilience (FAO, 2021a). Mobile cash transfers are an especially promising anticipatory action that expedite support directly to the most vulnerable households [NF1, NF2, PW1] (Guimarães Nobre et al., 2019; Premand and Storffler, 2020). These are shown to reduce livelihood disruption and increase the capability and agency of affected individuals to self-manage risk (Devereux and Jere, 2008). Similar applications of 'forecast-based action', enabled by 'forecast-based financing', equally show positive ROIs for drought interventions indexed by seasonal rainfall forecasts (Brown et al., 2014; Coughlan de Perez et al., 2015; Guimarães Nobre et al., 2019). These occupy a similar conceptual space to anticipatory action but with a more explicit focus on using physical drought indicators to threshold ex-ante interventions [PW1] (Guimarães Nobre et al. 2023; Tozier de la Poterie et al., 2023).

Most anticipatory action projects during drought remain dependent on socio-economic monitoring indicators for setting action trigger thresholds, instead of hydrometeorological indicators of physical drought [NF2, ND3].

"when food security enters 'alert', you know it is probably a good time for anticipatory action. And then when it's 'alarm', you know the crisis is now so humanitarian response is happening."

-NF2

For example, FAO (2021) anticipatory action case studies for droughts in Sudan and Colombia use livestock and human migration as predicting indicators for triggering actions. The United Nations Office for Humanitarian Affairs (OCHA) has also developed high profile anticipatory

action projects for drought in Somalia, Ethiopia, Chad, Burkina Faso and Niger, however, these all use food security Integrated Phase Classifications (IPC) as part of their financing thresholds for anticipatory actions (CERF, 2021b; OCHA, 2023c). A forecasted IPC 'crisis' stage among 30% of the population is the minimum trigger level for anticipatory action in Ethiopia (CERF, 2021b). IPC classifications are primarily assessed by committee, using increases in socio-economic indicators of food insecurity such as malnutrition, food prices, disease and migration data to guide classifications [NA1, NA2, UA2, NF1]. Therefore, these anticipatory action funds are being triggered by indicators of drought impacts that have already reached a severe level [PW1, NA2, UA1, UA2]. Whilst these projects are, to an extent, anticipatory of a major famine or humanitarian disaster, they set thresholds that trigger many months beyond the initial onset of physical drought [PW1, UA1, UC2]. Therefore, physical drought can impact socio-economic livelihoods for months before any anticipatory actions are taken [PW1, ND5, PW3, PW4, UA1, UA2, NA1, NA2].

"the triggers are set too high in a way, so that they don't really trigger any action until the drought's at quite a serious level. So it's not really forecast based, and it's not really anticipatory either."

-PW1

"we need to think about what those anticipatory actions really are for a drought, because building new boreholes in areas where water supply has already failed does not really count."

-ND5

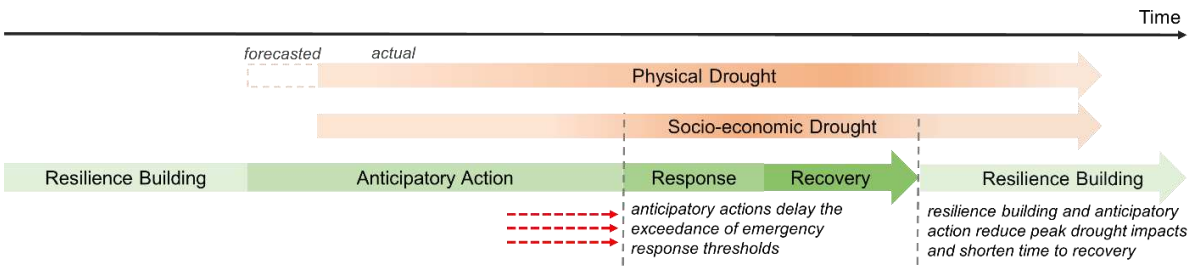


Figure 4.5. An updated conceptual framework for drought management, formalising the convergence of traditional DRM concepts with the pragmatic conceptual innovations of anticipatory action and resilience building.

To address the conceptual issues of traditional DRM terminologies, and to formalise the position of conceptual innovations that better reflect modern drought management activities and objectives, an updated framework for drought DRM is proposed (Figure 4.5). The anticipatory action window commences following the forecast of a meteorological and physical drought. It continues throughout the early period of physical and socio-economic drought, until significant proportions of the population experience increased water or food insecurity for common drought response thresholds to be exceeded [UC1; PW1, ND5] (Coughlan de Perez et al., 2015). In the framework, I show that the mitigating effects of anticipatory actions should delay the onset of response threshold-exceeding socio-economic drought, whilst reducing its peak intensity and duration (Figure 4.5; OCHA, 2023c; Weingartner and Wilkinson, 2020).

"there was a forecast that the upcoming rainy season was going to be poor… we then produced an anticipatory action plan jointly with the government to try to address some of those concerns and to try to get anticipatory actions in place before the upcoming rainy season."

-UC1

To mitigate water and food insecurity for the most vulnerable during drought, anticipatory actions are urgent following early signals of drought to attempt to prevent shortages before they arise [PW3, PW4, UW1, UW2, UW3, NW1, NW2] (Wens et al., 2021). Therefore, given that socio-economic drought indicators respond to precedent water and food shortages, it is hydrological indicators of physical drought such as rainfall, soil moisture and groundwater levels that will provide the earliest evidence to index anticipatory actions in advance [A2, MN1, NA1, NF1, ND2, UA1, UW3, PW4]. Then, as physical drought progresses, increasingly confident hydrological indicators and early changes in socio-economic indicators of drought impacts can be used to evidence the scaled-up financing of anticipatory interventions before emergency response thresholds are reached [PW1, UC1, NA1, UA1, UA2].

4.5.2 Shifting Towards Resilience Building

In the updated framework, the conceptual redundancy between preparedness and anticipatory action and the conceptual overlap of preparedness with the concept of mitigation are also addressed (Staupe-Delgado and Kruke, 2018). Resilience building encapsulates the DRR concepts of prevention, mitigation and preparedness, and it is increasingly being used to replace them in literature and drought management practice (Hemond and Robert, 2012; IFRC, 2016).

In Table 4.1, all activities coded to ‘prevention’, ‘mitigation’ and ‘preparedness’ can also be aptly described as resilience building activities according to its definition (UNDRR, 2016).

> *“Resilience: The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management.”*
>
> - UNDRR (2016)

The adoption of the resilience concept has benefits in drought management applications, as it is more people-centred than concepts of prevention, mitigation and preparedness, whose definitions focus on the hazard (Chang and Shinosuka, 2004; Hemond and Robert, 2012; IFRC, 2016). Its use shifts the focus of management towards managing long-term vulnerability and exposure, through actions tailored to the context of local livelihoods [UA1] (Lewis, 2013; Wens et al., 2021).

There are also practical benefits to the openness and inclusivity of resilience building as a concept, compared to using more precise categories of pre-disaster actions (MacAskills and Guthrie, 2014). DRM stakeholders approach drought risk reduction from a range of perspectives, with differing objectives all related to building resilience in some part of the socio-ecological system to drought (MacAskills and Guthrie, 2014; Needham, 1975). The resilience building concept accommodates different perspectives and local contexts, encouraging holistic projects and coordination between stakeholders towards a common, unifying goal of increasing drought resilience (Blauhut et al., 2022). The resilience concept also has critiques, notably the common assumption that management seeks to maintain a steady state during a disaster, and its potential confusion in practice with the concept of climate change resilience (IFRC, 2016). However, acceptance of resilience as being contextual alleviates these issues (MacAskill and Guthrie, 2014), whilst also encouraging those applying the term to examine the local context in more detail when designing DRM activities [UA1] (IFRC, 2016; Sudmeier-Rieux, 2014).

4.6 Actioning the Framework

An updated theoretical framework is only pragmatically useful if it can be applied in practice, and formalising terminology alone does not reverse decades of underfinanced disaster risk reduction.

Ex-ante drought interventions have been underfinanced for manifold reasons (Chapter 3), with the paucity of local monitoring and forecasting data a major factor [NA1, ND3, NE1, PW3, UA1, UA2, UC1, UC2, UW4]. The scarcity of high-resolution, accurate hydrological data bottlenecks anticipatory actions in the early phases of drought, as there is insufficient evidence of drought severity and potential impacts to justify their financing at scale [UC2, NF1, NF2, A1, A2, NA1, NA2, ND2, ND3, NE1, NE2, NW1, PW1] (Chapter 3). Currently, anticipatory actions that are using hydrological variables as trigger indices mostly use coarse-resolution, satellite-based monitoring of rainfall, soil moisture and vegetation data (CERF, 2021b; FAO, 2021a). This low-resolution, high uncertainty data contributes to low-confidence forecasts of drought, as well as low-confidence assessments of how physical drought will impact the many variables of socio-economic drought [ND2, ND3, ND5, NW4, PW3, UA2, UC1, UW1, UW2] (Hansen et al., 2022). Low-confidence forecasts cause a lower 'hit-rate' for ex-ante interventions, meaning a greater proportion of the anticipatory actions taken are later assessed to be 'false alarms' that were not needed [NF1] (Guimarães Nobre et al., 2019). This reduces the ROI of anticipatory actions indexed and triggered solely through hydrological indices, causing humanitarian organisations to await more confident socio-economic indices to trigger anticipatory action projects at a later phase of the drought's development [NF1, NA1, NA2, UA1, UA2].

"food security problems stem from water availability issues. Because of this linkage we need to collect hydrological information in a more upscaled manner."

-ND3

High-resolution hydrological data and analysis of how physical drought generates socio-economic drought can be used to confidently forecast future humanitarian needs and the subsequent benefits of taking anticipatory actions [A2, MN2, NA1, NE2, NF1, PW5, UA2, UC1, UC2, UW1]. This creates an evidence-base for early financing through rapid, index-based mechanisms that use pre-positioned financing [A1, MN3, NA1, NA2, ND1, UA1, UC2].

"if the shallow wells are showing a very serious downward trend getting close to zero, then that is a very good way of anticipating a major crisis because households will then either move, or their women will have to start walking huge distances. And all their demand will transfer to strategic boreholes, which may be much further away. With water monitoring data, you can anticipate that that's going to happen in advance."

-PW1

Standardising the monitoring of anticipatory actions also creates an international evidence-base of their value, by enabling ex-post evaluations of their ROIs and benefits to the individuals reached [NF1, NA1, UA1, UA2, UC2, PW3, PW4] (Clarke and Dercon, 2016; Weingartner et al., 2020). Expanding the evidence-base of anticipatory action's value therefore incentivises its investment, if investors have a more confident expectation of the ROIs and impacts that an anticipatory action project will have [NF1, NA1, UA1, UA2, UC2, PW3, PW4]. Furthermore, making the evaluation of anticipatory action projects standard practice ensures that the implementing organisation can publicly communicate the benefits of their proactive investments and actions [NF2, UA2]. It is a significant incentive for most institutions if they can quantify the value of their actions and justify that their money is being spent well when reporting to financing donors, investors or the public [UC2]. Publicly communicating innovative and proactive projects also improves their public and professional images, incentivising further investment in these actions and inspiring other organisations in the same sector to replicate proactive methods (Depoorter, 2006; Wilkinson, 2012).

Longer-term drought resilience building activities, especially those managing water resources, can use hydrological data to justify their financing in the same model. For example, to attract investment in the rehabilitation of boreholes to increase long-term drought resilience, local hydrological and socio-economic data can provide evidence to calculate the expected benefits of rehabilitation relative to the costs [UW3, UC2]. Equally, once rehabilitated, continuous monitoring of how the borehole has benefitted the community enables investing organisations to communicate the benefits of the project back to donors, managers or the public [NW2, PW3, PW4, MN1, MN2].

High-resolution hydrological monitoring data, therefore, is an enabler for resilience building and anticipatory drought interventions from their initial planning through to their financing. If these data are collected alongside the adoption of a clearer, contemporary drought management framework, the framework can demarcate a genuine transition towards proactive drought management practices. There is now, therefore, a need for more research into how hydrological

monitoring systems can be upscaled in drought-vulnerable areas that are historically data scarce (Chapters 5 and 6).

4.7 Conclusions

The evidence of conceptual issues in existing drought management frameworks presented in this study necessitates three key updates to the common framework.

First, evidence of conceptual barriers to applying agricultural and hydrological drought definitions for DRM activities means drought phases should be omitted from frameworks, in favour of the open concepts of 'physical' and 'socio-economic' drought. The relative timing of individual drought stages is variable, difficult to quantify, and, according to interviewees, their categorisation is unnecessary for the planning, implementation or evaluation of drought DRM activities.

Second, an updated DRM framework aims to clarify the position of anticipatory action in the temporal window between a physical drought's first forecast and the onset of humanitarian response. These actions can explicitly mitigate the forecasted socio-economic impacts of physical drought before they arise. Anticipatory actions can be made earlier if they are triggered by indicators of physical drought instead of socio-economic indicators, as the latter requires a significant degree of drought impacts before their anomaly can trigger interventions. However, physical drought-triggered anticipatory actions will be more scalable, with greater returns on investment (ROIs) if higher-resolution hydrological monitoring datasets can be collected to set more confident action thresholds for DRM interventions. These datasets can also be used to evaluate anticipatory actions ex-post, with evaluated case studies generating evidence to incentivise greater long-term investment in anticipatory action projects and their pre-positioned financing mechanisms.

Third, the updated framework proposes the replacement of prevention, mitigation and preparedness in the drought risk management framework with a single phase of resilience building. This resolves the redundancy between these terms and the unclear role of the preparedness concept, whilst increasing the management focus on people-centred interventions. The openness of the term is inclusive for different stakeholder perspectives, and it is more applicable to different situational contexts. Resilience building actions that improve

water supply resilience also require higher-resolution hydrological datasets for their planning, valuation and evaluation to incentivise investment.

The advantages of resilience building and anticipatory action over response are now broadly understood among academics and practicing DRMs, and this study addresses their absence from common drought management and DRM frameworks. However, commitments to these ex-ante actions will also require concurrent commitments to local hydrological data collection to support their planning and financing at scale.

5 Localizing Hydrological Drought Early Warning using In Situ Groundwater Sensors

Modified from a Water Resources Research publication with corresponding authors (Veness et al., 2022):

W. A. Veness, A. P. Butler, B. F. Ochoa-Tocachi, S. Moulds & W. Buytaert

5.1 Abstract

Drought Early Warning Systems (DEWSs) aim to spatially monitor and forecast risk of water shortage to inform early, risk-mitigating interventions. However, due to the scarcity of in-situ monitoring in groundwater-dependent arid zones, spatial drought exposure is inferred using maps of satellite-based indicators such as rainfall anomalies, soil moisture and vegetation indices. On the local scale, these coarse-resolution proxy indicators provide a poor inference of groundwater availability. The improving affordability and technical capability of modern sensors significantly increases the feasibility of taking direct groundwater level measurements in data-scarce, arid regions on a larger scale. Here, I assess the potential of in-situ monitoring to provide a localized index of hydrological drought in Somaliland. I find that calibrating a lumped groundwater model with a short time series of groundwater level observations substantially improves the quantification of local water availability when compared to satellite-based indices. By varying the calibration length, I find that a 5-week period capturing both wet and dry season conditions provides most of the calibration capacity. This suggests that short monitoring campaigns are suitable for improving estimations of local water availabilities during drought. Short calibration periods have practical advantages, as the relocation of sensors enables rapid characterization of a large number of wells. These well simulations can supplement continuous in-situ monitoring of strategic point sources to setup large-scale monitoring systems with contextualized and localized information on water availability. This information can be used as early warning evidence for the financing and targeting of early actions to mitigate impacts of hydrological drought.

5.2 Introduction

Drought-prone regions host many of the world's least developed countries, which are experiencing increasing drought risk due to population pressures and increasing drought frequencies (UNDRR, 2015). This is especially evident in Somalia, where estimated fatalities from the 2011 drought exceeded 250,000, and a further drought in 2017 required humanitarian assistance for 6 million people (FAO 2018, FAO, 2019). Drought Early Warning Systems (DEWSs) aim to monitor and forecast drought risk, enabling early interventions that mitigate the most severe socio-economic impacts. These interventions are often called 'resilience building', 'anticipatory', 'early' or 'forecast-based' actions, which have all demonstrated a capability to mitigate drought's most intense humanitarian impacts (Chapter 4). However, to enable the planning and financing of these actions at scale, DEWSs require higher-resolution evidence of drought intensity and community exposure to more confidently estimate the present and future socio-economic impacts of droughts (UNDRR, 2015; Brown, 2014). Hydrological monitoring of drought is historically challenging (Chapter 3.5; Chapter 6) and requires innovative approaches to improve the datasets available to DEWSs.

5.2.1 Current Drought Monitoring Methods for Early Warning

A range of regional-scale, satellite-based indicators are currently used to monitor physical drought development. The Standardized Precipitation Index (SPI) is a popular indicator for monitoring meteorological drought (McKee et al., 1993; Van Loon, 2015). The SPI indicates rainfall anomaly compared to the long-term average for that chosen time period (Sheffield et al., 2014). For agricultural drought (Van Loon, 2015), satellite-based indicators are used such as soil moisture and the Normalized Difference Vegetation Index (NDVI; Liang et al., 1994; NASA Worldview, 2022; Tarpley et al., 1984). These indicate available soil moisture for vegetation growth, which in turn indicates crop failure in areas where agriculture is non-irrigated (Brown, 2014; FEWS NET, 2023; FSNAU, 2023a; Sheffield et al., 2014). However, in most arid zones during late dry seasons, water availability for human consumption depends on groundwater supply. As such, these surface indicators are not ideal for assessing hydrological droughts – the most intense form of drought that causes water shortages (Kumar et al., 2015; MacAllister et al., 2020; Tallaksen and Van Lanen, 2004; Van Loon, 2015). Nevertheless, these same satellite-based indicators of meteorological and agricultural drought

are used by DEWSs to infer the spatial intensity of hydrological drought by proxy because of a paucity of direct groundwater observations (Brown, 2014; FSNAU, 2023a; FEWS NET, 2023; Kalisa et al., 2018; Kumar et al., 2015; Sheffield et al., 2014; UCSB, 2021).

In practice, these indicators show abnormally large declines during the early stages of drought (Kchouk et al., 2021), and thus provide some evidence to trigger a national or regional early warning at a good lead-time ahead of the highest intensity phase of drought. However, despite useful lead-times, the spatial accuracy of these indicators is low due to the coarse resolution and measurement uncertainty of the satellite-data used as inputs (FSNAU, 2023a; Sheffield et al., 2014; Karnieli et al., 2010; Sheffield et al., 2014). Furthermore, the extent to which seasonal changes in these indicators reflect actual underlying groundwater levels is unknown – aquifer recharge and well recovery depends heavily on drainage basin characteristics and human activity. As a result, these coarse physical drought indicators are used by practitioners with caution when determining which communities are most locally exposed to hydrological drought and therefore at risk of water shortages (Karnieli et al., 2010; Kchouk et al., 2021; MacAllister et al., 2020; Okpara et al., 2017).

During drought development, these physical indicators are viewed alongside seasonal climate forecasts from international organizations such as the GHACOF (Greater Horn of Africa Climate Outlook Forum), the Famine Early Warning Systems Network (FEWS NET), the National Oceanic and Atmospheric Administration (NOAA) and the UK Met Office, which give a low-certainty prediction of how the drought may evolve in future months (Brown, 2014; FEWS NET, 2023; FAO, 2021b; Dinku et al., 2018; Mwangi et al., 2014). For shorter-range forecasts, the popular United States Geological Survey's Early Warning Explorer (USGS EWX) tool provides open access to the latest 15-day pentadal rainfall forecasts (UCSB, 2021). Meteorological forecasts are also compromised by a low spatial resolution and high uncertainty, particularly at longer lead-times. Furthermore, the scarcity of national hydrological monitoring programs in Sub-Saharan Africa prevents national agencies from augmenting these forecasts with local data (Brown et al., 2014; Stephens et al., 2016). Therefore, combining low resolution indicators of physical drought intensity with these forecasts results in high uncertainty about current and future drought exposure at the local scale (Boluwade, 2020; Dinku et al., 2018; (Kumar et al., 2015; Pappenberger et al., 2005).

As a result of these limitations, drought managers, including national agencies and international NGOs, depend on national socio-economic data to spatially monitor drought exposure through evidence of drought impacts (FAO, 2018; FSNAU, 2023a). These data are the primary source of information used to plan and finance early interventions with prioritized communities (Brown, 2014; Buchanan-Smith and McCelvey, 2018; FSNAU, 2023a; Stephens et al., 2016). In Somalia and Somaliland, this information is made available in real-time by the United Nations Food and Agriculture Organization's Food Security and Nutrition Analysis Unit's (UN FAO FSNAU) Early Warning Early Action dashboard (FSNAU, 2023a). It presents monthly data on market prices, livestock prices, migration data, disease prevalence, wages and nutrition. For example, by October 2016, when the socio-economic impacts of the 2016/17 drought first became apparent, the socio-economic indicators had reached the 'alarm' phase over 200 times across all of Somalia's administrative regions, over double the previous year's level (FSNAU, 2023a).

Socio-economic data is fundamental for monitoring vulnerabilities to drought (Brown et al., 2014; UNDRR, 2015); however, an over-dependence on socio-economic data for monitoring real-time drought exposure is problematic for DEWSs. Requiring signals from socio-economic drought impacts for an early warning to be triggered means that opportunities for early, water shortage-mitigating interventions have already been missed. A further limitation is the coarse spatial and temporal resolution of the socio-economic indicators, with monthly data aggregated by FAO FSNAU in Somalia for each administrative region (Brown et al., 2014; FSNAU, 2023a). This has the effect of smoothing out localized drought impacts, to the extent that DEWSs have little information on relative exposure at the community level. This can lead to poorly targeted and ill-timed interventions which fail to mitigate water shortages and the cascading secondary impacts of malnutrition, economic losses, community displacement, famine and conflict in the most exposed regions (Brown et al., 2014; FAO, 2014; MacAllister et al., 2020; Stephens et al., 2016).

5.2.2 Modern Sensors for In-Situ Groundwater Monitoring

The limitations of using regional methods to monitor hydrological drought exposure illustrate the need for alternatives. Despite advice in 2003 by UN FAO that data on groundwater-level fluctuations are "essential as a basis for management" (FAO, 2003), methods to monitor drought still widely omit in-situ groundwater data (Lewis and Liljedahl, 2010). Reasons have

included the high economic cost of data collection, the labor-intensive nature of monitoring, difficulties with community participation and a lack of hydrological expertise to process the data (Ajoge, 2019; Calderwood et al., 2020; Frommen et al., 2019; Pozzi, 2013).

Advances in sensing technology have reduced the cost and complexity of in-situ monitoring to a level where it can now be implemented on an unprecedented scale (Buytaert et al., 2016; Calderwood et al., 2020; Paul and Buytaert, 2018; Open Geospatial Consortium, 2021). Modern automatic sensors have lower costs, greater accuracy, higher-frequency measurements, real-time telemetry, longer battery lives and now require less labor and expertise for installation and data processing (Calderwood et al., 2020; Paul and Buytaert, 2018). However, the long-term maintenance of in-situ sensors remains resource intensive. Therefore, in proposing a scalable method for groundwater monitoring, understanding the optimal duration of in-situ data collection for useful and cost-effective monitoring is crucial.

Here, I explore whether short-term, high frequency monitoring can be used to calibrate a groundwater model sufficiently to enable accurate, scalable simulations of groundwater availability, using a case study of three abstraction wells in Maroodi Jeex, in the self-declared independent republic of Somaliland. The paper is structured as follows. First, I describe the groundwater model and calibration procedure. Then, by varying the calibration length between 1-30 weeks, I assess the value of additional calibration weeks for model performance. From this, a 7-week calibration is used to evaluate how effectively the model simulates observed groundwater availability compared to satellite-based proxy indicators. The calibrated wells are then simulated between 2015-20, to illustrate how the model can be used to index hydrological drought during the 2016/17 and 2019 Horn of Africa drought events. This is followed by a discussion of how this method can be scaled-up to a large number of wells, and how the information can be used to inform the planning of early and effective interventions during droughts.

5.3 Methods

5.3.1 Modelling approach

In data-scarce regions, simple conceptual groundwater models are favored over process driven models (Beven, 2001; Mackay et al., 2014). Here, I use a modified version of the quasi-physically based AquiMod model to simulate the local water table in response to satellite derived rainfall and evapotranspiration rates (Mackay et al., 2014). The model (fully described in Supporting Information; Chapter 5.7) provides a simple and efficient method to simulate time-dependent well water levels based on a conceptual representation of groundwater systems, with a parameter set small enough to deploy automated calibration procedures at low runtimes (Beven, 2001; Mackay et al., 2014). Model inputs, comprised of daily rainfall and actual evapotranspiration values for an area surrounding the pumping well, were obtained from satellite data (Maidment et al., 2017; Sheffield et al., 2014). The model was calibrated against in-situ groundwater-level data using a Monte Carlo approach (Mackay et al., 2014; Pianosi et al., 2015).

5.3.2 Input Data

Daily precipitation and actual evapotranspiration data for the period 2015-2020 were obtained from, respectively, TAMSAT (Tropical Applications of Meteorology using Satellite Data; Maidment et al., 2017) and AFDM (African Flood and Drought Monitor; Sheffield et al., 2014). For point-scale applications, there is higher uncertainty associated with the daily rainfall product when used at its finest 4 km spatial resolution, particularly when employing temporal downscaling from the initial 5-day cumulation product. To reduce this uncertainty, we averaged daily rainfall over a 40 km square (Maidment et al., 2017). Daily AFDM actual evapotranspiration data has a spatial resolution of 27 km. The lower spatial variability of evapotranspiration means it is associated with less uncertainty than the rainfall input (Sheffield et al., 2014). Average evapotranspiration over 54 x 54 km was calculated for model input.

Groundwater levels at 15-minute intervals were obtained using pressure transducers in three shallow, large-diameter wells in Maroodi Jeex, Somaliland. Shallow wells provide an ideal target for DEWSs because they typically run dry before deeper boreholes and thus display an earlier drought signal in rural areas (MacAllister et al., 2020). Sensor installation took place on 21 July 2017, at sites < 10 km apart (Figure 5.1).

The selected wells, although geographically close, displayed markedly different behavior due to differences in local geology, construction and usage (Figure 5.4b, 5.4c & 5.4d). Although they sit within a common unit – a weathered, unconfined section of the Upper Cretaceous Yesomma (Nubian) Sandstone – local differences in porosity, conductivity and specific yield were observed due to regional interfingering of clastic and carbonate facies (Ali, 2009, FAO SWALIM, 2021). This heterogeneous aquifer was therefore a suitable location to test the modelling approach under varying unconfined aquifer properties. A 7-month time series of data was collected for the three wells, which reflected some of the outstanding challenges of continuous data collection in this environment including logistics, battery supply and staffing (Paul and Buytaert, 2018). The three datasets were each used for separate calibrations of the modified AquiMod model.

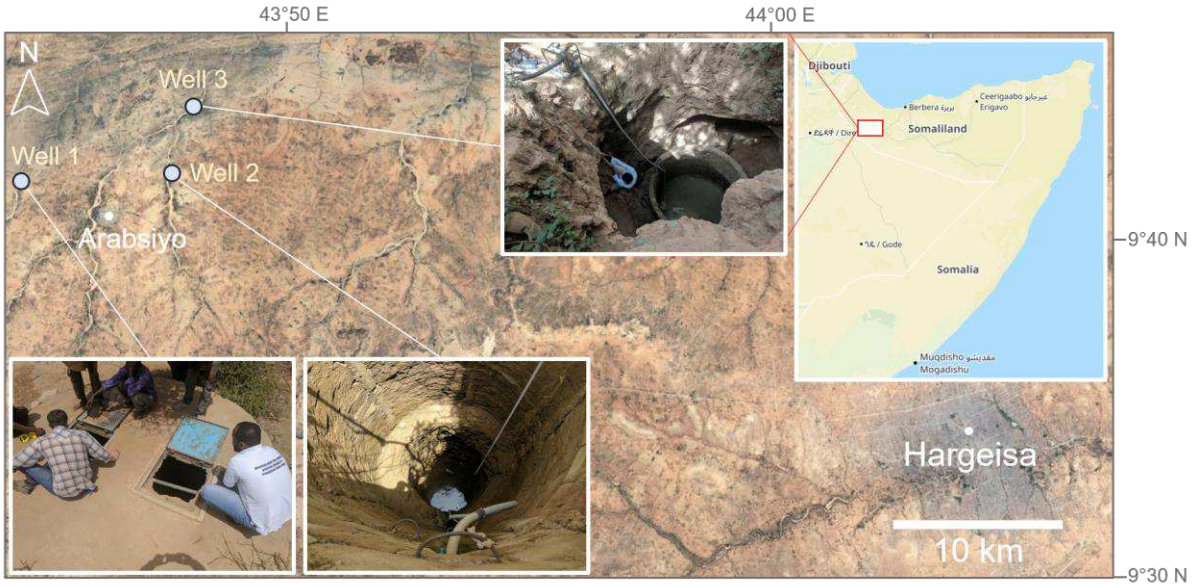


Figure 5.1. Location of the three shallow, large diameter wells in Maroodi Jeex, Somaliland.

5.3.3 Groundwater Model

I use a modified form of AquiMod (Mackay et al., 2014) to estimate aquifer recharge (R) and calculate groundwater drainage (Q_g), outputting a daily water balance for the well. The unconfined (saturated) aquifer module is represented as a single locally homogeneous and isotropic layer, above which is an equally homogeneous unsaturated module that is, in turn, overlain by a soil module (Figure 5.2). Precipitation (P) enters the top soil module following

losses due to actual evapotranspiration (AE). If the soil moisture (SM) exceeds the maximum soil moisture capacity (SM_{max}), the surplus water becomes soil drainage (SD) to the unsaturated zone module. This drainage is then delayed by being distributed over time using a Weibull distribution to provide recharge (R) to the saturated module. In the saturated container, recharge from soil drainage is the sole input.

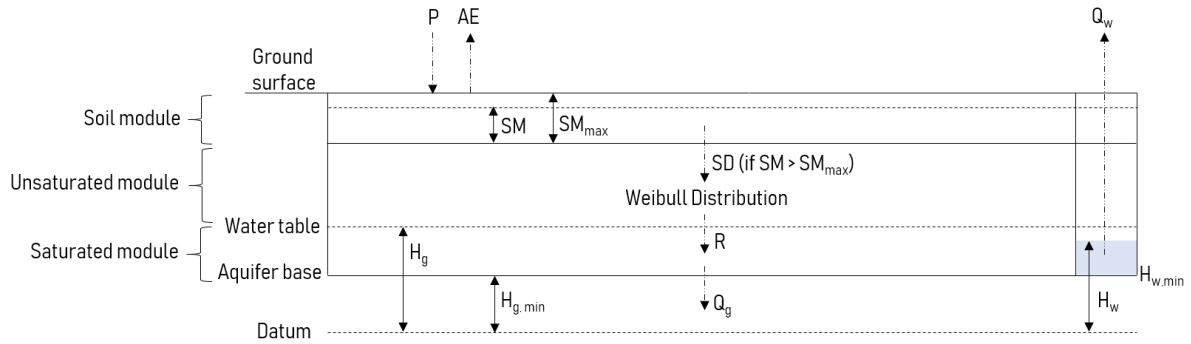


Figure 5.2. Modified AquiMod lumped catchment regional model for a single unconfined aquifer layer.

The main output is the volume of groundwater drained (Q_g), which represents losses from the local groundwater system through regional processes. This assumes that the groundwater level drains from the system at a rate proportional to its height (H_g) above the minimum drainage level ($H_{g,min}$; Cuthbert, 2014). In this study, Q_g is adapted from the single layer AquiMod model in Mackay et al. (2014), by lumping the parameters used to calculate its value. This allows the model to be reduced to a single vertical spatial dimension (Figure 5.2), where Qg is calculated according to the difference in the height of the groundwater level (H_g) above the base of the aquifer ($H_{g,min}$, which is set equal to the pump inlet depth, $H_{w,min}$, as this is the 'effective' locally accessible depth of aquifer) factored by a time constant 'τ' [day 1]. Therefore, 'τ' is an empirical, lumped parameter open for calibration, representing the combined effects of groundwater flow from well to outlet, aquifer leakage and nearby abstractions that can all combine to decrease the local water level (Mackay et al., 2014). This simplification removes the need to represent groundwater flow using Darcy's law and thus avoids needing to define hydraulic conductivity and distances to outlets on the boundary of the model. It improves the feasibility of a short calibration period by removing two additional parameters from the procedure, which in turn increases the sensitivity of τ to improve the calibration (Beven, 1989). The model conceptualization and the adapted equations are fully described in the Supporting Information (Chapter 5.7).

Equation 1 calculates the change in groundwater level (H_g) for each timestep, by dividing the balance between the total recharge (R), drainage (Q_g) and well-abstraction (Q_w) by specific yield (S_y) and a nominal area around the well (A):

$$\frac{dH_g}{dt} = \frac{R - Q_g - Q_w}{S_y A} = \frac{r - q_g}{S_y} - \frac{Q_w}{S_y A} = \frac{r - q_g}{S_y} \quad (1)$$

If the area is sufficiently large whereby |R| & $|Q_g| >> |Q_w|$, as is common in shallow wells with low abstraction volumes, then the impacts on the regional groundwater level due to abstraction from the modeled well can be ignored and the recharge and groundwater drainage can be modeled as fluxes (r & q_g, respectively). Equation 1 is then discretised using an explicit forward difference scheme and integrated on a time step of one day, using daily recharge values obtained from the soil and unsaturated zone modules. This gives a continuous daily time-series of the unpumped groundwater level elevation (H_g) for each well site (Figure 5.4b, 5.4c, 5.4d; Veness et al., 2022).

5.3.4 Calibration Method

I calibrated the model using Monte Carlo and Global Sensitivity Analysis (GSA) methods (Ochoa-Tocachi et al., 2018; Pianosi et al., 2015). Following sensitivity analysis, I focused on calibrating 4 sensitive parameters, while setting the remaining parameters to fixed values estimated from prior understanding of the aquifer and general hydrological systems. I sampled 10,000 combinations from a uniform distribution using Latin Hypercube Sampling (LHS; McKay et al., 1979). Input ranges were set following a manual calibration and an initial scoping study of parameter sensitivity.

In this study, the AquiMod calibration is modified so that $H_{g,i}$ is calibrated to the maximum water level in the observed data for day 'i' ($H_{w,i,max}$). In abstraction wells, pumping causes partial recovery (H_w) to the unpumped water table (H_g). This difference is at a minimum following well recovery, immediately before the onset of the following abstraction event. Therefore, calibrating $H_{g,i}$ to these daily observed peaks in groundwater level changes H_g to a simulation of 'available groundwater level' in that well. This requires an assumption that daily partial well recoveries reach a constant distance from the natural unpumped water level, which was considered appropriate based on the observed well recoveries. In datasets where $H_{g,i} - H_{w,i} \neq$ constant, this method can be coupled to a pumping model to include the effect of variable abstraction rates on the modelled water level (see Supporting Information; Chapter 5.7). For

example, given the variable abstraction drawdowns and partial recoveries seen in Well 3 (Figure 5.4d), coupling a pumping model may improve the fit in future implementations.

5.3.5 Calibration Length Analysis

To assess the relationship between calibration length and model performance, the calibration period was varied at weekly intervals between 1-30 weeks. The Root Mean Square Error (RMSE) score was calculated for the full 30-week combined calibration and validation period each time (Pianosi et al., 2015). This method highlights an 'optimal' calibration period within the 30-week range for groundwater modelling in this context, if additional weeks of in-situ observations have diminishing value in improving model performance and the challenges of monitoring outweigh the benefits. Following this, as explained in the results (Chapter 5.4.1), a 7-week calibration was selected as a suitable duration and used for further analysis.

The best scoring parameter sets from the 7-week calibrations at each well (4.5-week for Well 3 due to a shorter dataset) were used in a 23-week validation (Table 5.1). The fit of the validations were compared to satellite-based indicators of NDVI, soil moisture and SPI-3 (Figure 5.4), as well as uncalibrated simulations of the original AquiMod model at each well that define literature derived parameter values (see Supporting Information in Chapter 5.7; Allen et al., 1998; Ascott et al., 2020; Domenico and Schwartz, 1990; FAO SWALIM, 2021; Jackson et al., 2016; Johnson; 1967; Lohmann, 1972; Mackay et al., 2014).

Table 5.1. Parameter input ranges, calibrated parameter values and RMSE scores for the top scoring 7-week calibration sets at Wells 1, 2 and 3.

Parameter	Units	Input Range (Well 1)	Calibration (Well 1)	Input Range (Well 2)	Calibration (Well 2)	Input Range (Well 3)	Calibration (Well 3)
Sy	-	0.05 – 0.12	0.0753	0.005 – 0.01	0.00720	0.025 – 0.045	0.0340
τ	day^{-1}	5e-4 – 1e-3	7.29e-4	$5e^{-5}$ – $1.5e^{-4}$	$1.02e^{-4}$	2e-4 – 4e-4	2.65e-4
k (Weibull)	-	3 - 15	3.67	3 - 8	5.24	3 - 30	19.0
λ (Weibull)	-	10 - 30	20.1	18 - 30	23.9	10 - 30	14.1
$H_{g\,(t=0)}$ (fixed)	m	1.17	1.17	1.9	1.9	1.65	1.65
SM_{max} (fixed)	m	0.005	0.005	0.005	0.005	0.005	0.005
$SM_{initial}$ (fixed)	m	0	0	0	0	0	0
$H_{g,min}$ (fixed)	m	0	0	0	0	0	0
RMSE (calibration)	m		0.0577		0.339		0.0423
RMSE (validation)	m	-	0.0997	-	0.982	-	0.218

Satellite-based indices were downloaded to compare how well they represent these observed groundwater levels by proxy. NDVI and Soil Moisture Active Passive (SMAP) data were downloaded at Well 2's coordinates from NASA Worldview (NASA Worldview, 2022), and daily SPI-3 values from Princeton's African Flood and Drought Monitor (Sheffield et al., 2014). NDVI is generated by the Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) instrument and downloaded in 16-day intervals at a 250 m spatial resolution (NASA Worldview, 2022). The SMAP layers show a daily composite of surface soil moisture in cm^3/cm^3, calculated by the Single Channel Algorithm V-Pol for the daily half-orbit passes by the SMAP radiometer and posted to the 9-km EASE-Grid 2.0 (NASA Worldview, 2022). SPI-3 is calculated from bias-corrected Multi-Satellite Precipitation Analysis (TMPA) and hybrid reanalysis data (Huffman et al., 2007; Sheffield et al., 2014).

5.3.6 Model Simulations during 2016/17 & 2019 Droughts

Using the same calibration parameters (Table 5.1), the models were simulated from January 2015 – December 2020 using historic rainfall and evapotranspiration as inputs (Sheffield et al., 2014; Maidment et al., 2017). The initial heads to start the model have been estimated by comparing January 2015 SPI-3/6/12 values with January 2018, for which there is corresponding observed groundwater level data, and assessing a likely groundwater level relative to the January 2018 level. The 2016/17 drought event is highlighted from the date the Somalia government declared drought (Guled, 2017) to the final observed rains of the following Gu rainy season. The 2019 drought is highlighted from the declaration date of drought emergency made by Oxfam (Barter, 2019), to the final Gu rains that year.

A critical level is defined for each well, below which the regular abstraction drawdowns observed during the dry season would not be possible. This is due to the water level falling below the pump inlet depth during abstraction drawdown, causing a 'dry pump.' A 'regular' dry season drawdown was calculated as the mean drawdown depth (m) during the final 50 observed dry season abstractions at each well. This value was then added to the pump inlet depth ($H_{w,min}$) to calculate the well's critical level.

5.4 Results & Discussion

5.4.1 Calibration Length Analysis

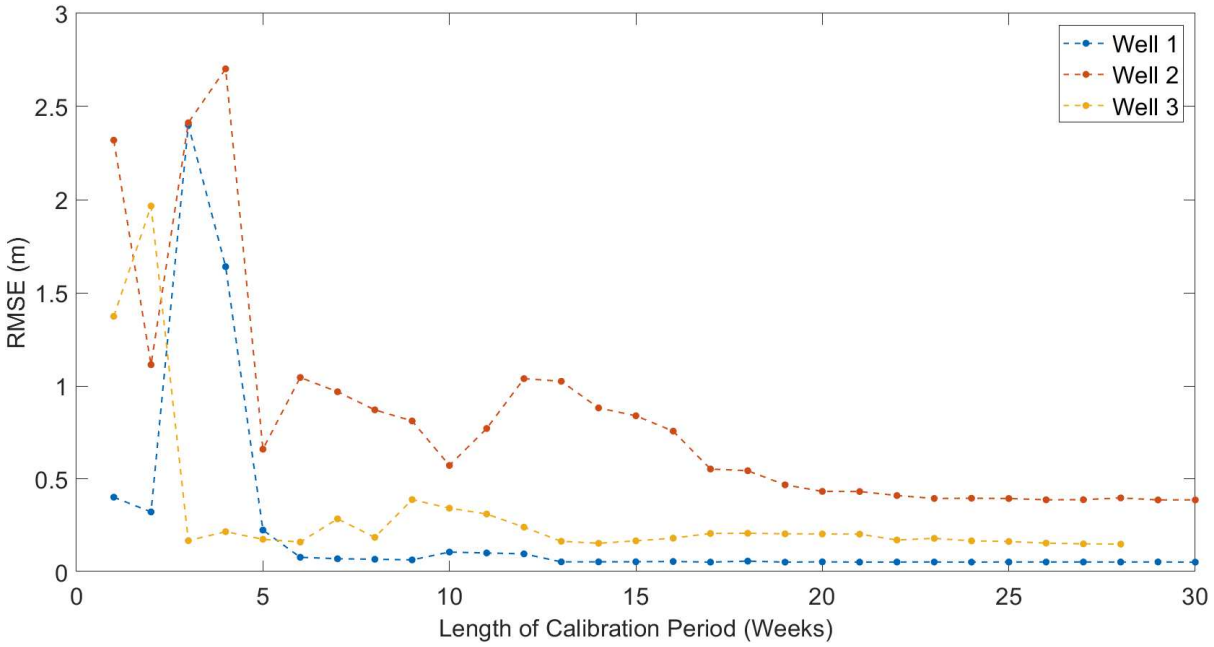


Figure 5.3. RMSE for the full calibration and validation period, with calibration lengths varied at weekly intervals.

The analysis shows that there is little further improvement in calibration performance after extending to 5 weeks (Figure 5.3). At this period (3 weeks at Well 3), the calibration window is long enough to include the start of the wet season, with groundwater level observations that have increased due to recharge. This causes the recharge parameters of Sy, λ and k to become sensitive and trained in the calibration. It is therefore essential to have a calibration period that captures observations from both the wet and dry seasons for sufficient calibration of the model. The remaining error in RMSE at the longest calibrations will be sourced from input inaccuracies from the rainfall and evapotranspiration data, as well as modelling uncertainty with processes uncaptured by the simple, lumped parameter model (Ascott et al., 2020; Mackay et al., 2014). Following this analysis, a 7-week calibration period, covering approximately equal intervals of dry and wet season conditions is selected as a suitable time window (Figure 5.4b, 5.4c & 5.4d). The three calibrated wells achieve an efficient fit to the observed water levels in validation, with RMSE scores of 0.0997 m, 0.982 m and 0.218 m respectively.

5.4.2 Model Performance

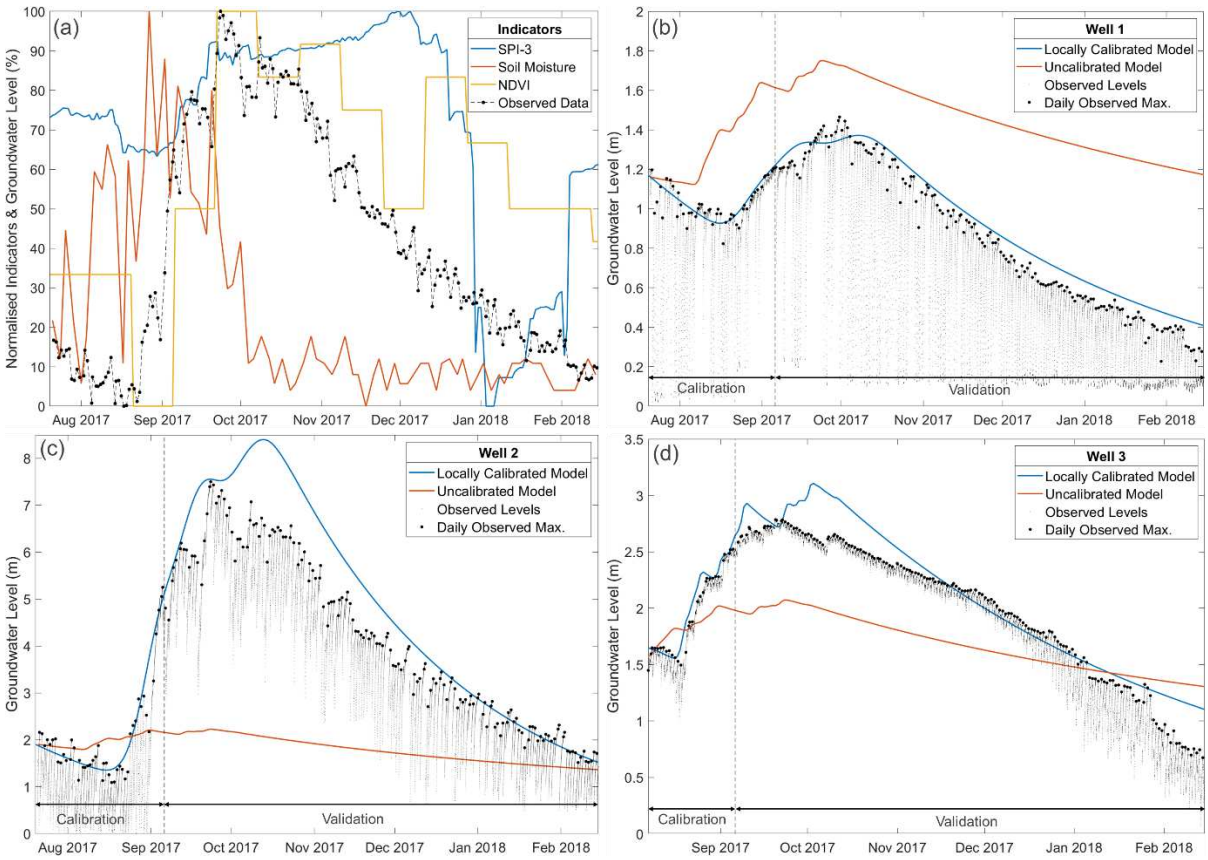


Figure 5.4. (a) Normalized satellite-based proxy indicators of physical drought intensity compared to Well 2's observed daily maximum water levels. Calibrations of (b) Well 1, (c) Well 2 and (d) Well 3 are shown to compare performance with the proxy indicators and an uncalibrated AquiMod groundwater model. Observed water levels and the corresponding calibration targets set at the daily maxima are shown for comparison of fit.

The satellite-based indicators (Figure 5.4a) are not suitable proxies of local groundwater level. Soil moisture approaches its minimum months before the observed wells and remains at a flat minimum level throughout the long dry season. SPI-3 represents rainfall anomaly instead of absolute rainfall, so is unlikely to follow groundwater levels closely due to its calculation (Kumar et al., 2015). NDVI shows the closest fit to observed groundwater levels, but it underestimates the dry season water level decline and suffers from a low temporal resolution. This potential for NDVI to misrepresent ground conditions was highlighted recently by UN FAO SWALIM, who removed it as a parameter from their Combined Drought Index DEWS platform, citing a "poor correlation" between NDVI and ground information (FAO SWALIM, 2022).

Compared to the regional indicators, the calibrated model provides a substantially improved representation of observed groundwater levels (Figure 5.4b, 5.4c & 5.4d). The locally calibrated simulations capture the unique response of each well to recharge and dry periods, giving a more reliable indication of water availability. In comparison, the poor performance of the uncalibrated groundwater model highlights the need for a local calibration, as literature-derived parameters fail to capture differences in well and local aquifer properties.

There are remaining limitations in the model performance, with compounding uncertainties from input data, lumped model design and the short calibration (Mackay et al., 2014). Although it is difficult to quantify the contribution of individual uncertainties to model error, validation tests of this approach when implementing it in a new region will highlight if there are local causes of significant error requiring factoring into the modular AquiMod model (Ascott et al., 2020). It is recommended to extend this validation testing in a sample of wells to multi-year durations, to assess if any inter-annual variabilities in aquifer or human behaviors affect the performance of parameters fixed by the short calibration. In any application, the outstanding uncertainty of simulations and the potential causes and effects of inter-annual variability must be carefully conveyed to users (Twomlow et al., 2022).

The required model performance depends on the use case and the specific decisions being informed by the real-time simulations (Maxwell et al., 2021; Twomlow et al., 2022; Zulkafli et al., 2017). This can be modified to an extent, by adjusting the model setup or extending calibration durations where practical. In some implementations, strategic wells within the simulated monitoring network may warrant continuous monitoring to reduce monitoring uncertainties further. However, in drought-prone areas where no groundwater information is currently available and communication between communities and intervening authorities are weak, short monitoring may provide best value and practicality for generating useful evidence to support early interventions by stakeholders who are increasingly adopting ‘no regrets’ approaches to anticipatory action (Lentz et al., 2020).

5.4.3 Simulating the 2017 & 2019 Droughts

To demonstrate the model’s use as a localized index of groundwater availability, the calibrated wells are simulated during the two most recent droughts in Somaliland (Figure 5.5). These

water levels are put into the context of local water availability by plotting each well's critical level, below which a full, regular abstraction drawdown would not be possible (Chapter 5.2.6).

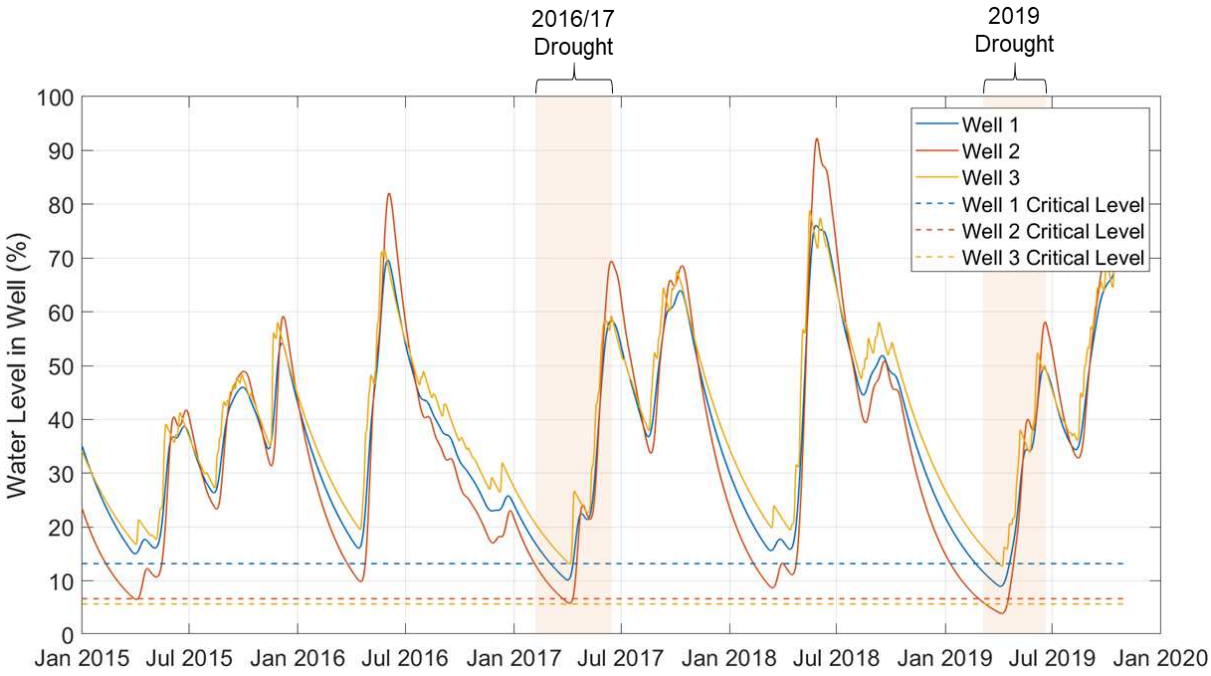


Figure 5.5. 2015-20 simulations of the three wells using the 7-week calibration parameters. Water levels are normalized to the distance between the top of the well and the pump inlet depth. The two droughts are indicated from the dates that humanitarian crises were declared by the Somalia president (2017; Guled, 2017) and Oxfam (2019; Barter, 2019). The critical level is the level below which the mean observed dry-season abstraction drawdown would not be possible due to water level falling below the pump inlet.

The lowest water levels are seen during the two documented droughts (Figure 5.5; Barter, 2019; FEWS NET, 2023; FSNAU, 2023a; Guled, 2017). Wells 1 and 2 fall below their critical level during the two droughts, indicating that regular abstraction drawdowns would have been restricted. Well 3 remained above its critical level throughout. This indicates that Wells 1 and 2 suffered abstraction shortages during the two droughts, which may have required interventions depending on the function of the well, the availability of alternative water sources and the socio-economic context of the community using it for water supply.

During long dry seasons where recharge is typically zero from January – early March (Figure 5.5, Maidment et al., 2017), this real-time visualization of water level decline enables a visual trajectory of the lead-time before the wells reach their critical levels. Users can also compare real-time water levels to simulations of water levels during previous drought years, such as

2017 (Figure 5.5), to contextualize the severity of the real-time water shortage with their experiences or understanding of previous droughts in that region (Campbell et al., 2021; Sword-Daniels et al., 2016). For both hydrologists and non-experts, this direct comparison connects an understanding of the potential impacts of current water shortages, as well as the actions that can be taken to mitigate them based on learned lessons (Hillbruner and Moloney, 2012).

Forecast inputs have not been explored here, as they suffer from high cascading uncertainties at lead-times beyond 1-week (Pappenberger et al., 2005; Walker et al., 2019). However, future development of this approach may explore the use of meteorological forecast data to simulate future water-levels. On a lead-time of 1-2 weeks, datasets such as the 15-day CHIRPS-GFES pentadal rainfall forecasts can be used (UCSB, 2021). If forecasting months ahead, seasonal forecasts from GHACOF (Mwangi et al., 2014) can be used to project future water levels under different rainfall scenarios. This can further support decision-makers in planning interventions, by translating how water levels will respond to upcoming surface conditions.

5.4.4 Discussion: Model applications for DEWSs

For DEWSs, maps and hydrographs of real-time water levels can be presented alongside simulated water levels during historic drought events to place the real-time hydrological drought intensity into context (Twomlow et al., 2022). Stakeholders with lived experience of previous droughts can then interpret the likely processes and socio-economic impacts that will arise from groundwater levels being higher or lower than previous drought years (Campbell et al., 2021; Hillbruner and Moloney, 2022). For national and humanitarian stakeholders, spatial maps of relative drought exposure can inform the national programming of anticipatory action and emergency response. Furthermore, with forecast-based financing systems in need of more evidence to confidently trigger earlier anticipatory financing release (Stephens et al., 2016), maps of drought exposure can be used to trigger the release of intervention financing. A recent growth in parametric insurance for drought, seeking to payout ahead of peak impacts based on hydrological parameter threshold exceedance, also suggests demand for groundwater availability as a localized parameter to index these policies (Okpara et al., 2017). For local stakeholders, access to localized, community-scale information enables actions that mitigate water shortages. Early interventions include site visits, advice and technical assistance, scaling

up proportionately to emergency water supplies, other lifestyle-sustaining supplies and cash transfers (Brown et al., 2014, Stephens et al., 2016; Wendt et al., 2021).

5.5 Conclusions

This study finds that groundwater models with short calibrations, in this case using just 7-weeks of wet and dry season observations, offer substantial improvements in quantifying local groundwater availability when compared to satellite-based indicators used to infer this by proxy (Brown, 2014; FEWS NET, 2023; FSNAU, 2023a; Kalisa et al., 2018; (Kumar et al., 2015; UCSB, 2021). Furthermore, by presenting water levels relative to each well's unique critical depth, the method provides a local and contextualized indicator that translates water levels to water availability (Kcouck et al., 2021; Sutanto et al., 2019).

By only requiring short observation periods, the barriers to scaling-up these methods in a national-scale monitoring system are reduced as the sensors can be relocated to calibrate a large number of wells (Paul et al., 2020). Taking short, high-frequency measurements, as completed here, also captures abstraction behaviors to enable contextualizing calculations of each well's critical water level. Although serious challenges and ethical considerations in implementation remain, such as monitoring system governance, sensor security and community consent to participation (Buytaert et al., 2014; Paul and Buytaert, 2018), this study highlights the renewed technical feasibility of large-scale groundwater monitoring for hydrological drought monitoring and early warning.

The methodology outlined in this report is deliberately parsimonious, and it aims to serve as a demonstration of technical feasibility upon which greater complexity can later be introduced. There are considerable limitations in these methods from a traditional hydrological modelling perspective, from input uncertainties to the lumping of model parameters and the use of empirical 'critical level' calculations (Mackay et al., 2014; Maidment et al., 2017; Sheffield et al., 2014). However, groundwater modelling in a data-scarce region is intrinsically bound to modelling limitations that cannot be resolved without collecting extensive field-data, and this is not a feasible requirement across a monitoring network in this context (Beven, 2001). Further

development of this approach should therefore focus on more validation testing of short calibrations in larger pilot schemes, whilst resolving the degree of uncertainty that is acceptable for users in guiding specific decisions and actions that mitigate water shortages (Zulkafli et al., 2017; Maxwell et al., 2021). Monitoring systems can then be designed that equilibrate practical feasibility with acceptable uncertainty and simulation accuracy (Maxwell et al., 2021).

Drought-prone, data-scarce regions such as the Horn of Africa are challenging environments for modelling, yet these areas can benefit the most from groundwater models to improve drought monitoring and early warning. Overcoming these challenges requires innovative approaches in both data collection and analysis to generate useful, decision-informing early warning information (Nature Sustainability, 2021). Therefore, this study proposes a viable method of generating a useful, localized groundwater availability index for DEWSs and anticipatory actions, that remains mindful of the fundamental requirement of a groundwater monitoring solution to be technically and practically feasible (Beven, 1989).

5.6 Data Availability Statement

The input data and model implementation are available online (https://doi.org/10.5281/zenodo.6631801).

5.7 Supporting Information

This supporting information document outlines the full details of the modified AquiMod model used in this study (Chapter 5.7.1 & Chapter 5.7.2; Mackay et al., 2014). Chapter 5.7.3 illustrates the presence of parameter sensitivity during the 7-week calibration. Chapter 5.7.4 provides the literature-derived parameter values used in Figure 5.4b, 5.4c and 5.4d plots of an uncalibrated AquiMod model at each well. Chapter 5.7.5 provides an example radial flow model that can be coupled with the AquiMod simulation in wells where abstraction drawdowns have high seasonal variability. Explanatory diagrams and text should be reviewed in the main paper prior to review of these methods.

5.7.1 AquiMod Recharge Model

The soil moisture storage (SM) is calculated by Equation 1. Any excess water at SM(t) above SM_{max} becomes soil drainage [m]:

$$SM(t)=\begin{cases}0 & \text{if } SM(t-1)+P(t)-AE(t)\le 0\\ SM(t-1)+P(t)-AE(t)-SM_{\max} & \text{if } 0<SM(t-1)+P(t)-AE(t)\le SM_{\max}\\ SM_{\max} & \text{if } SM(t-1)+P(t)-AE(t)\ge SM_{\max}\end{cases} \quad (1)$$

$$SD(t)=\begin{cases}0 & \text{if } SM(t-1)+P(t)-AE(t)-SM_{\max}\le 0\\ SM(t-1)+P(t)-AE(t)-SM_{\max} & \text{if } SM(t-1)+P(t)-AE(t)-SM_{\max}>0\end{cases} \quad (2)$$

The input to groundwater storage, soil drainage (SD; Equation 4), is modified by a time and head-dependent delay to give the recharge rate at time *'t'* (r_t) [m/day]. The time-delay is defined by the Weibull probability density function, which is a two-parameter function (Equation 3). The λ parameter controls the position of the peak recharge, while k is a time constant [day^{-1}] that dictates the density of the recharge distribution around the peak (Mackay et al., 2014).

$$f(x,\lambda,k_{wei})=\begin{cases}\dfrac{k_{wei}}{\lambda}\left(\dfrac{x}{\lambda}\right)^{k_{wei}-1}e^{-(x/\lambda)^{k_{wei}}} & \text{if } x\ge 0\\ 0 & \text{if } x>0\end{cases} \quad (3)$$

where: f is the probability distribution, x is the Weibull time step, $k_{wei} > 0$ is the shape parameter, and $\lambda > 0$ is the scale parameter of the distribution.

The recharge is calculated using Equation 4, where 'r_t' is the recharge, 'α' is a scaling parameter, '*f(x)*' is the Weibull probability density function, '*SD*' is the soil drainage [m], 'x' is the Weibull timestep following soil drainage input [day] and 't' is the overall timestep [day].

$$r(t)=\alpha\sum_{i=1}^{n} f(x,\lambda,k_{wei})\cdot SD_{t-x+1} \quad (4)$$

5.7.2 Modified AquiMod Groundwater Model

Consider an arbitrarily large area A [L^2] surrounding an abstraction well in a near surface unconfined aquifer. Let $H_g(t)$ [L] represent the mean height of the regional water table above a

datum at the end of day t, and $H_{g,min}$ [L] represent a groundwater drainage outlet at the base of the aquifer. Given that the depth of the shallow alluvial aquifer is unknown for all wells in this study, $H_{g,min}$ is assumed to be at the aquifer base, which is set equal to the base of the well to assume a fully-penetrating well. Assume that the loss of water from the aquifer Q_g [L^3T^{-1}] is a linear function proportional to the height of the water table above the outlet (Equation 5), where τ is a decay time constant that can be calibrated by the observed data [T^{-1}].

$$Q_g(t) = \begin{cases} A\tau\left(H_g(t-1) - H_{g,\min}\right) & \text{if } H_g(t-1) - H_{g,\min} > 0 \\ 0 & \text{if } H_g(t-1) - H_{g,\min} \le 0 \end{cases} \quad (5)$$

The total daily recharge [L^3] is given in Equation 6, where $r(t)$ is the output from the soil water model [L].

$$R(t) = Ar(t) \quad (6)$$

The total daily abstraction volume is $Q_w(t)$ [L^3]. If the specific yield of the aquifer is given as S_y [-], then the daily change in groundwater storage is described by Equation 7.

$$\frac{dH_g}{dt} = \frac{R(t)}{AS_y} - \frac{Q_g(t)}{AS_y} - \frac{Q_w(t)}{AS_y} \quad (7)$$

Equation 8 describes the daily change in regional water table in response to a 1-dimensional recharge (r), groundwater drainage (q_g) and well-abstraction (q_w). In this study, long term head change due to well-abstraction volumes is assumed negligible when A is large, so q_w is set to 0. Solving the ODE in Equation 8 can create a continuous time-series of the local water table elevation.

$$\frac{dH_g}{dt} = \frac{r(t)}{S_y} - \frac{q_g(t)}{S_y} - \frac{q_w(t)}{S_y} \simeq \frac{r - q_g}{S_y} \quad (8)$$

As the input P and AE data are a daily rate, a daily value for the water elevation (H_g) at the start of each day ('t') in the data collection period is calculated. This is achieved by discretizing

Equation 8 and using an explicit forward difference scheme, integrated on a time step of one day. This outputs a continuous daily time-series of the water elevation (H_g) for each well.

5.7.3 Parameter Sensitivity During 7-week Calibration Procedure

The dotty plots show the sensitivity of the parameters during the 7-week calibration of Well 2 (Figure 5.6a), with the convergence of lower RMSE calibration scores towards a specific parameter value indicating sensitivity of the model performance to that parameter's value. The other dotty plots offer a comparison with the same input ranges for Well 2 following a 7-month calibration (Figure 5.6b). This indicates that the parameter *'k'* is not sensitive, but it does show that the 7-week calibration does not constrain τ as well as a 7-month calibration.

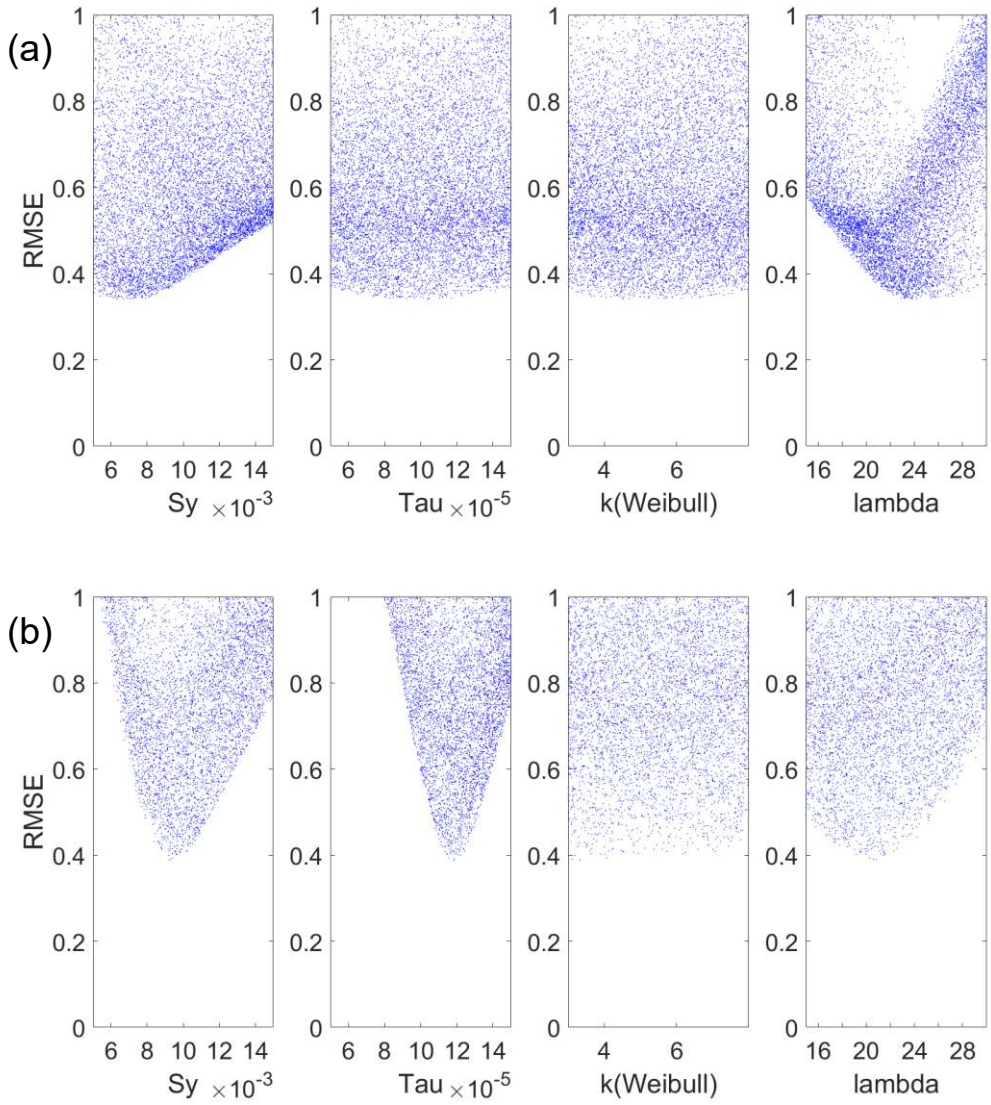


Figure 5.6. Dotty plots showing RMSE scores for parameter input values during (a) a 7-week calibration and (b) a 30-week calibration at Well 2.

5.7.4 Literature-derived Parameters for Uncalibrated AquiMod Model

The calculation used original equations from Mackay et al.'s single layer model (2014). Daily water levels (H_g) were calculated using literature derived parameter values and an understanding of the wells' locations in the alluvial, unconfined aquifer (Table 5.2; Mackay et al., 2014; Ascott et al., 2020; Jackson et al., 2016; Allen et al., 1998; FAO SWALIM, 2021; Lohmann, 1972; Johnson; 1967; Domenico and Schwartz, 1990).

Table 5.2. Parameter values used in uncalibrated AquiMod model simulations.

Parameter	Units	Uncalibrated Model
Sy	-	0.1
K	$mday^{-1}$	25
k (Weibull)	-	3.5
λ (Weibull)	-	3.5
$H_{g\ (t=0)}$ (fixed)	m	variable
SM_{max} (fixed)	m	0.005
$SM_{initial}$ (fixed)	m	0
$H_{g,min}$ (fixed)	m	0
X – Boundary Dist.	m	100
Y – Boundary Dist.	m	100

5.7.5 Example Radial Flow Abstraction Model for Coupling to AquiMod

This section provides an example radial flow model that was used in experiments to include seasonal variations in abstraction rates to the simulation of groundwater levels in the well. To investigate this, we used a numerical solution of the radial flow equation for a finite diameter well. Employing the Dupuit-Forchheimer approximation for radial flow to a well, where there is spatially uniform but time varying recharge and aquifer drainage, gives Equation 9.

$$\frac{\partial h}{\partial t} = \left(\frac{Kh}{S_y}\right)\frac{1}{r}\frac{\partial h}{\partial r} + \left(\frac{Kh}{S_y}\right)\frac{\partial^2 h}{\partial r^2} + \frac{r}{S_y} - \frac{q_g}{S_y} \tag{9}$$

We assume a far boundary condition of constant head, as the radius of the system is large. The near boundary condition is derived from the water balance at the well, which has a constant radius of r_w and a (time dependent) pumping rate of Q_w, hence (Equation 10):

$$\pi r_w^2 \frac{\partial h_w}{\partial t} = 2\pi r_w K h \left.\frac{\partial h}{\partial r}\right|_{r=r_w} - Q_w \quad \text{or} \quad \frac{\partial h_w}{\partial t} = \frac{2Kh}{r_w} \left.\frac{\partial h}{\partial r}\right|_{r=r_w} - \frac{Q_w}{\pi r_w^2} \tag{10}$$

This gives the boundary condition for the model as (Equation 11):

$$h \left.\frac{\partial h}{\partial r}\right|_{r=r_w} = \frac{r_w}{2K} \frac{\partial h_w}{\partial t} + \frac{Q_w}{2\pi r_w K} \tag{11}$$

The equations (9) and (10) are solved in MATLAB using a finite difference representation of the radial differentials, which are integrated over time using ODE solver ode15s. Logarithmic spacing was used to provide nodes closely spaced near to the well and becoming progressively further apart away from the well. The code was verified against the analytical solution of Papadopoulos and Cooper (1967).

The input value and duration of Q_w was estimated from observed drawdowns during wet and dry seasons enabled by the high-frequency data, and knowledge of the wells' dimensions and volume. The value of K was manually calibrated using observations of best-fit with the drawdown and recovery curves.

6 Unlocking the Benefits of Groundwater Data

6.1 Abstract

The global scarcity of high-resolution hydrological monitoring data is a well-known constraint to sustainable water resources management (WRM), especially in low- and middle-income countries. However, an understanding of the benefits of hydrological data and clear practical pathways to collecting these data is still missing in the case for their investment. Here, the beneficiaries of groundwater data are scoped through inductive interviews of 42 expert stakeholders based in the Horn of Africa, who also assess the outstanding barriers to monitoring and their potential solutions. The benefits of groundwater data are mapped for 18 different user groups. Groundwater data is found to support a systemic change in decision-making among WRM user groups, evolving water management towards evidence-based, proactive and more decentralised processes. Emergent user groups with no prior experience of groundwater data also identify potential value for a range of applications, including forecast-based humanitarian financing, drought early warning, and parametric insurance indexing. To overcome monitoring challenges and realise these benefits, automated data collection and analysis through improved, cost-effective monitoring sensor technologies and investment in WRM capacities is required. To guide implementation, the paper concludes with a 5-stage framework for sustainably scaling decision-integrated groundwater monitoring systems. The implementation framework advises thorough preparation, procurement and piloting to design user-centred monitoring and communication networks where data collection is institutionalised, informed WRM is decentralised, and operational systems are sustainably financed and governed.

6.2 Introduction

Groundwater is the primary source of clean water in Sub-Saharan Africa, and it remains an abundant resource across the continent (Ford et al., 2022). However, fragile water infrastructure and low-capacity water resource management (WRM) mean that over 350 million people have no access to basic water services (Grafton et al., 2023; UN-Water, 2022). Cyclical droughts repeatedly expose the fragility of groundwater supply systems, causing mass displacement and disastrous humanitarian impacts (FEWS NET, 2023; Kreibich et al., 2022; MacAllister et al., 2020). These same supply systems now face unprecedented pressure from intensive abstraction and climate variability (Ascott et al., 2022; He et al., 2021; Scanlon et al., 2023).

Despite groundwater's established value (UNESCO, 2021), the state of most aquifers and boreholes are unquantified due to the absence of any long-term, high-resolution groundwater monitoring networks (IGRAC, 2020; World Bank, 2018). This paucity of monitoring means a fundamental evidence-base for informed WRM is missing in Sub-Saharan Africa (Foster et al., 2012; Garrick et al., 2017; Gaye and Tindimugaya, 2018; FAO, 2003; UNESCO, 2021; UNESCO, 2022). This contributes to WRM institutions being trapped in processes of reactive management for water supply shortages, unable to transition to evidence-based planning of more resilient, sustainable solutions (UN-Water, 2022; Garrick et al., 2017; Gaye and Tindimugaya, 2018).

The issue of groundwater monitoring data scarcity has been identified as a barrier to development and humanitarian drought management in Chapter 3, and the issue is now being highlighted on the international platform. "Making the invisible visible" was the slogan and primary focus during the 2022 United Nations (UN) Water Summit on Groundwater (UNESCO, 2022; USAID, 2022), which set the groundwater dialogue ahead of a landmark 2023 UN-Water conference (Ovink et al., 2023). Groundwater data is now being acknowledged as an important ecosystem service that improves WRM practices value to with potential further value for social, economic and environmental well-being (Pandeya et al., 2016; Ovink et al., 2023).

However, like other hydrological variables, detailed valuations have not yet been completed to elucidate its value in full to potential users (Dasgupta, 2021; Pandeya, 2021; UNESCO, 2021).

Furthermore, investment in groundwater monitoring remains scarce following numerous monitoring projects that have failed to scale after facing manifold implementation challenges (Foster et al., 2012; IGRAC, 2020; Pavelic et al., 2012; Sarni et al., 2018; World Bank, 2020; Adelana, 2009). In these projects, monitoring networks are rarely maintained properly for technical and financial reasons (Calderwood et al., 2020; IGRAC, 2020). Further challenges in processing, digitising, and communicating data means users also typically see few outputs from the process. A lack of sustained, useful output has gradually caused a general decline in interest for in-situ groundwater monitoring (World Bank, 2020).

However, disruptive technologies present an opportunity to resolve implementation barriers (Schwab, 2017; Sarni et al., 2018). Emerging groundwater monitoring technologies and the Internet of Things significantly improve the viability of integrated, long-term groundwater monitoring (Calderwood et al., 2020; Kombo et al., 2019; MacAllister et al., 2020; Sarni et al., 2018). More capable and cost-effective wireless sensors can now automate the collection and transmission of groundwater data over Sub-Saharan Africa's growing telecommunication networks (Chan et al., 2020; Serele, 2018; Solinst, 2021). Furthermore, as explored in Chapter 5, dedicated data platforms can automate complex methods of data processing, analysis and communication, thus reducing the technical and staffing burden of generating useful insights from the data for relevant stakeholders (Sarni et al., 2018). An increasingly technologically capable public, and an improving professional understanding of how to implement monitoring, for example, through citizen science approaches, further improve viability (Nath and Kirschke, 2023). An ever-improving technical capacity of water authorities means they are increasingly well placed to host these systems (Gale and Tindimugaya, 2018; Serele, 2018; FAO SWALIM, 2023; World Bank, 2022b).

However, despite accelerating technical opportunity, monitoring investment remains low and there remains no detailed valuation or clear cost-benefit basis to incentivise investors (Chapter 3; UNESCO, 2021; Kumar et al., 2010; Garrick et al., 2017). Qualitative methods are pre-requisite to quantitative valuations to ensure that the deductive designs of quantitative valuations capture the full scope of users for which the data has potential value. Therefore, this study completes a pre-valuation qualitative scoping of the potential beneficiaries and their respective applications for groundwater data, before evaluating the mechanisms that currently prohibit the resolution of groundwater data scarcity. Through interviews of 42 expert stakeholders based in the Horn of Africa and subsequent thematic coding analysis (Chapter 2),

the study first maps the benefits of groundwater data access to 18 different stakeholder groups, implicitly assessing positive value (benefits) as progress toward the Sustainable Development Goals (SDGs) framework (United Nations, 2015; Pandeya et al., 2021; UNESCO, 2021). It then assesses the challenges of setting up groundwater monitoring networks, and it concludes with a 5-stage implementation framework that advises how to overcome these challenges and develop scalable systems that can realise the data's full potential value to users (Maxwell et al., 2021).

6.3 Results and Discussion

6.3.1 Mapping the Benefits of Groundwater Monitoring Data

The qualitative scoping results detail the benefits of groundwater monitoring data for 18 different stakeholder groups, including users that are Water Resource Managers (WRMs) as well as emergent users with no prior experience of groundwater data. As an overview, groundwater-data provides WRMs with detailed, regular evidence of aquifer and water infrastructure status. These data can flag supply issues in need of urgent short-term interventions, whilst informing the long-term development of more resilient supply infrastructure in productive aquifers, where water infrastructure is maintained by stakeholders that are held accountable through shared monitoring data. WRMs also gain system-wide benefits through collaborative groundwater monitoring that builds knowledge-capacities and improves stakeholder inter-relationships. Emergent stakeholders gain a new evidence-base for triggering early drought, humanitarian and water management financing, among a range of other applications, if groundwater data can be communicated to their information needs and levels of data literacy.

6.3.1.1 Benefits for Water Resource Managers (WRMs)

6.3.1.1.1 Local Water Authorities

Local water authorities such as district water bureaus, basin authorities and private cooperatives extract value from groundwater data for day-to-day operational management, decisions on local crisis management, new well installations and long-term water supply planning.

For new well installations, monitoring evidence of aquifer productivity helps to site more resilient sources at strategic sites [MD1, MN2, MD2]. New well specifications can be optimised to the aquifer based on monitoring data from nearby wells for best efficiency and yield [A3, MN1, MN2, MD2, NF1, PW5].

"if we actually have this information on aquifer performance, we can start to triangulate between the boreholes to work out where the yields are going to be good. Then you can site your new boreholes there, instead of waiting for the water running out to tell you who needs the next one."

-PW5

For the management of existing water sources, near real-time access to groundwater level and quality information enables local authorities to make early interventions, instead of waiting for failure reports by word-of-mouth to act [MN1, UW3]. Recurrent borehole failures are endemic in the Horn of Africa - borehole functionality was at 55% and 60% in Ethiopia and Kenya respectively during the 2016-17 drought (MacAllister, 2020; Thomas et al., 2021).

"some kind of data is a totally fundamental prerequisite for any action – you can't have informed, proactive action without the data being there."

-NW2

With assistance from Non-Governmental Organisations (NGOs) and the national water authority, early interventions by the local water authority include: pumping and technical advice, private sector negotiation, equipment supply, water purification, borehole rehabilitation, new borehole drilling, water trucking, subsidies and cash transfers [MN2, MN3]. These anticipatory interventions have a system-wide positive financial return on investment, as these interventions are cheaper, less staff intensive, less disruptive and more lifestyle-sustaining than the expensive and complex practical solutions needed when a water source fails (MacAllister et al., 2020).

"this year we drilled 6 boreholes, all up to 370 m depth at $600 per metre, but they have all failed in this area – all 6."

- MD5

It is a common misconception that borehole failures are mostly caused by droughts and over pumping [PW4]. Instead, most failures stem from poor borehole siting, bad equipment and poor construction methods [ND4, ND5, PW4, UW2].

"*water levels are dropping in the aquifer! It's the first thing that the community says when its borehole fails. But it's probably failed because it was drilled by a Mickey Mouse contractor who designed and structured it badly."*

-PW4

The absence of monitoring and post-construction pumping tests prevents confident diagnosis of why each borehole is failing [PW4]. It is often therefore "simpler" [MD5] to abandon the borehole in favour of constructing another nearby that may be prone to the same problems [MD5]. A lack of failure diagnosis prevents accountability for the root cause of failures. For instance, if a failure was caused by corner-cutting during the drilling process, this can be diagnosed after initial monitoring pumping tests and drillers can be held accountable [PW5, PW4; NW2, UW2, MN3, MD1]. If a failure is caused by over-pumping, this can be interpreted from monitoring data and communicated to the users during borehole rehabilitation to prevent reoccurrence [NW2].

"*in communities there can often be different ideas about what is causing problems with water supply; there can be different views… that's also why this groundwater data is essential to try and understand what's really, really causing the problems."*

-NW2

"what is causing the shortages at so many shallow wells and boreholes? If you monitor it, then everyone actually knows what is causing that. And then you make policies to change that."

-NW5

Groundwater monitoring enables accountability for the human root-causes of failures by making evidence available, and it clarifies the benefits of investing more to ensure boreholes are constructed by reputable contractors and drilling supervisors [NW2, NW5, MN2] (Klassert et al., 2023). With greater aquifer knowledge and accountability among stakeholders, professionalisation in the local water sector is encouraged (Danert et al., 2020). By taking a more active role in cooperative monitoring at the local community level, the local water authority also gains greater trust and future cooperation with the communities it serves [PW4, NW2].

"if they see the local government are more engaged with them, and possibly improving service at the village level, then there's a big incentive for community volunteers to provide support."

-NW2

6.3.1.1.2 National Water Authorities

National water authorities, as close partners to local water authorities, share much of the benefits experienced at district-level but on a larger scale of management. However, experts expect further value to pooling data to the national level. Databases of water levels, quality and aquifer performance can inform a more equitable long-term spatial planning of national water infrastructure to ensure water supply is strengthened in the least resilient areas [A3, MD2, MN1, MN2, MN3, PW5].

"it tells us which areas are going to be having pressures. Then what strategies can we put in place to address those pressures? Could groundwater depletion occur? Maybe we can do artificial recharge. Are there areas where we can [have] conjunctive use of groundwater and surface water? Does it need water trucking or new infrastructure?"

-MN1

In drought, spatial maps of well performance and water stress can assist with water and WASH (Water Agriculture Sanitation and Hygiene) needs assessments [MN1, A2, ND3, MD2]. With high-confidence, granular and real-time evidence of specific communities and water sources that require WASH and lifestyle-preserving interventions, resources can be allocated in priority of need. High-confidence, more detailed proposals about finance needs can then also ensure these actions are funded earlier and at larger scale by the government and donor organisations [MN1, A2, NF1, NF2]. This timely financing can be distributed to the local and district water authorities for proactive WASH interventions that mitigate supply failures [MN1, A2]. Together with the provision of finance and data, the national authority can provide advisory frameworks for integrating data into decentralised, local decision-making to ensure information translates to action (Welle et al., 2016).

"if an area dependent on groundwater is under pressure, then you're going to use [monitoring information] to mobilise resources and combat that. In the long term, if people realise that it's a resource being depleted, they might make the investments before those on the ground suffer."

-MN1

To support the process of increased accountability and professionalisation in WRM, groundwater data provides an evidence-base for a national authority to enforce drilling and supervision standards [PW5, NW5]. Professionalised and accountable local WRMs unlocks a decentralisation of aquifer management from the central authority to those with local experience, knowledge and connections [PW2, PW4, MN1] (Danert et al., 2020). By freeing

up its staff from field engineering projects, this enables the national authority to more formally adopt a coordinating, legislating and resource managing role that manages a wider professional network of WRMs [UW1, NW5].

Transparent sharing of groundwater data can also improve inter-district and international relations at transboundary aquifers, where disputes can arise over unsubstantiated accusations [ND4, NW5, NW2]. Whilst it may expose agreement violations in the short term [NW2], a collaborative sharing of data and management of transboundary groundwater can shift these from areas of tension and conflict to areas of co-development, trade, enterprise and sustainable resource management (Nijsten et al., 2018; Sanchez, 2022).

6.3.1.1.3 Non- & Intergovernmental Organisations (NGOs & IGOs) in WASH

In their technical support role to public and private authorities, non-governmental WASH (Water, Sanitation and Hygiene) teams often have a greater technical capacity to extract interpretations from groundwater data and strategically advise on long-term aquifer development [ND2, NE1, NF1, NF2, NW5, PW4, UW2]. The data can contribute to rigorous aquifer assessments for new borehole siting and identification of areas experiencing unsustainable groundwater decline to anticipate humanitarian needs [ND1, UW1, NE1, PW1, UA1, MD3, MD4, NW5, UW2].

"we want to monitor all the strategic water sources. They're the boreholes where we want to know where they are located and how they're functioning. You know, we take some important parameters from these boreholes because we want to be ahead of the people and even the drought emergency response team to tell everyone where the water is."

-UW1

"this data will tell us where water levels are reliable and where they become low during droughts. This data can also help us when the drought is not occurring to review the places that ran out of water and say, yes, we should build more boreholes or water infrastructure there for next time."

-ND2

During drought, WASH teams can use forecasts from real-time groundwater data and subsequent modelling to secure backup water supply in areas forecasted to have impending shortages through water trucking, water purification, emergency well construction and other technical support [ND2, ND3, NW1, NW5, UC2 UW1, UW2, UW3, UW4]. Furthermore,

given their role in Internally Displaced People (IDP) camp construction and management, WASH advisors can use existing aquifer data to site camps in sustainable locations with more reliable water access [PW5, MN1].

6.3.1.1.4 UN & NGO Emergency Response

Groundwater data can provide a new index to spatially program anticipatory action and drought emergency response according to water and WASH needs [A1, A2, NA1, NA2, NE2, NF1, NF2, NW1, NW2, UC1, UW1, UW3, UW4]. Compared to existing early warning and humanitarian programming platforms, groundwater information is water resource specific, more localised and can be monitored in real-time (Gure, 2021; Veness et al., 2022). This information can also support existing platforms by triangulating, calibrating and validating coarser satellite indicators of drought intensity [NA1, NA2, NE2, NF1].

"it would be useful to help form a drought response plan"

-UC1

Alongside other indicators in common aid frameworks (FEWS NET, 2023; FSNAU, 2023b), groundwater levels and quality can be used to trigger interventions and their financing once they exceed or are forecasted to exceed thresholds [A2, MN1, NA1, ND2, NF1, PW1, UA1, UW3]. Whilst this information can initially guide anticipatory action at the start of drought, it can continue to guide emergency humanitarian response by highlighting communities and districts suffering the greatest water shortages. With the displaced typically the most vulnerable to food insecurity, the ability to anticipate displacement and subsequent migration routes is considered useful [A1, ND3, NE1, NE2, PW1, UA1], as emergency response can be targeted towards those areas [PW1, PW3, UA1, UW1].

"it's useful for trying to map out where your anchor sources are, as it helps you understand where people are going to be migrating to during the dry season"

-UA1

6.3.1.1.5 Local Communities

Whether governed by a community water management committee, private suppliers or public-private partnerships, local community WRMs benefit from regular data and relevant analysis of their individual water sources [NW1, NW2, NW3, UW1, UW2].

Issues in water level, yield and water quality can be flagged by monitoring before source failures occur [UW2], leading to rationing, alternative water sourcing and other resilience building actions [NW1, MD3]. Information on borehole and shallow well water performance also forms a basis for negotiation up to the district level, where transparent aquifer data for the surrounding region can help community members find backup water sources nearby in the event of local well failures [A3, MD3, NW1].

For pastoralists, data sharing can lead to more informed dialogue and planning over nomadic migration routes towards aquifers and point sources proven to have extra capacity [UA1, UW2]. For agricultural and agro-pastoral farmers, forecasted water availability based on existing groundwater levels can also inform the planning of crop sowing, offtake collection and herd size management [PW3].

Wider local community benefits from participation in groundwater monitoring include job opportunities, roles for women and a professionalised water sector that creates economic multiplier effects among WRMs [ND4] (Danert et al., 2020). Furthermore, groundwater monitoring data collection, sharing and co-development of solutions improves the trust relationship between local communities and government, leading to greater geopolitical stability by setting a foundation of collaboration for the public good [NW2, MD3, PW2, PW3].

6.3.1.2 System-wide Benefits for WRMs

6.3.1.2.1 Capacity Building

Close collaboration with technical partners for setting up monitoring networks transfers technical skills to water authorities and community members, creating better capacity to make evidence-based, proactive management decisions [MN1, NW1, NW2, MD4] (Scheihing et al., 2020). Groundwater information sharing also prompts discussions about data interpretation and subsequent actions that naturally transfer knowledge and skills [NW2]. Pre-analysed information that's accessible to non-expert and emerging stakeholders can increase their

engagement and familiarity with technical groundwater considerations as well [NW2]. However, this transfer of knowledge requires dedicated funding to create spaces and networks for capacity building [A2, MN1, MN2, MN3, NA2, NE2, NF1, NF2, NW3, PW3, UA1, UA2, UC1, UW2, UW3, UW4].

"it is about systems strengthening because, if we are able to strengthen the capacity of the relevant water authority to monitor water resources across the region, it becomes easier for them to timely respond and timely advocate for resources."

-NW2

6.3.1.2.2 Communication, Coordination & Trust

"*if you want to develop conditions of trust and accountability, you need to work with actual practical resources to establish environments of cooperation rather than conflict."*

-PW3

In areas of weak governance, collaborative groundwater monitoring and water resource management can be a foundational step for further collaboration in WASH and other areas of development [PW3, PW4, PW5]. With data sharing, a pathway for communication and dialogue is established between community, government and influential local stakeholders [NW5, GO1, A2]. This can improve coordination towards common goals, mobilising local experts, community members and private stakeholders [NW1, NW2, GO2, MD4, MN1]. Over time, as personal relationships and a culture of trust are developed, synergies and society resilience to conflict can also increase [NW1, NW2] (Peters et al., 2021).

6.3.1.3 Benefits for Emerging Stakeholders

6.3.1.3.1 NGO & UN Advocacy, Analytics & Financing

Groundwater monitoring data can be used as an index to improve the feasibility of earlier, larger and more accurate financing of drought anticipatory actions (Chapter 3), by providing a more confident indication of areas in need of early inventions. It can equally encourage anticipatory actions to have a clearer focus on securing strategic water points than existing anticipatory action schemes, which have a predominant food security focus [A2, MN1, NA1, ND2, NF1, PW4, UA1, UW3]. These actions can have significant positive returns on

investment, as they can mitigate community displacements and other cascading secondary impacts that result from water shortages [UA1] (Gumucio et al., 2022).

"I know that OCHA [the UN Office for Coordination of Humanitarian Affairs], for their anticipatory action framework, are trying to identify context specific indicators that they can trust for use as trigger points for releasing extra funds."

-NA1

"I could see myself adding this to the presentations that I'm already doing, and then that would help inform kind of the advocacy and the larger scale resource mobilisation relating to drought response. Both from a food security standpoint, but also I think, on the water and sanitation standpoint."

-UC1

6.3.1.3.2 Parametric Insurance & Commodity Traders

Agricultural and drought parametric insurance schemes are yet to scale in Sub-Saharan Africa, primarily due to a high basis risk - there is a low accuracy and spatial resolution in the existing satellite-based parameters used to index areas experiencing drought stress [ND2, NF1]. High-resolution monitoring of groundwater levels has the potential to lower basis risk by taking a direct, objective measure of hydrological drought intensity at points of water abstraction [NW2]. From farmer-scale to national-scale policies, groundwater data can provide a new index for more financially viable and scalable insurance policies [NF1]. Agricultural commodity traders and their information providers can also use groundwater data as a predictor of future crop harvests and political risk, as groundwater levels are likely to correlate with these and provide a predictive index months in advance [NA2, NE1].

Any open-access information would be used by traders, analysts and brokers to inform investments that stay ahead of the market to make profit [NA1]. Public information can also inform a largely free-market global food system of impending shortages that can encourage investment in supplying food to areas where demand is expected to increase [NF2]. Given the unknown potential externalities of influencing global commodity flows like this, more research is required into the benefits and risks of providing this information to global markets, as well as the ethical implications of providing access to elements of local community-hosted data.

6.3.1.3.3 Academics, Scientists & Experts

High density, long-term groundwater monitoring networks would create new research opportunities in hydrology, hydrogeology, climate sciences and socio-hydrology. WRMs in this study proposed interest in projects investigating aquifer recharge relationships with heavy rainfall events [UA1], studies of the degree to which groundwater data can be generalised for different aquifers [MN3] and the impacts of sand dams or other managed recharge schemes on water tables [A3, PW3]. WRMs also propose practical studies on the reliability of citizen science groundwater monitoring [NW2], studies of the extent to which communities can use groundwater data [NW2] and studies on how water authority technical capacities can be improved to integrate groundwater data into management processes [GO1]. Some WRM focussed academics are interested in quantitative analysis, using the data to calibrate and validate local or global predictive models for hydrological modelling and forecasting [PW3, A1].

Emerging stakeholders suggest research areas concerned with the correlation between groundwater and other sociological parameters. They are interested in how groundwater shortages generate food shortages [A1, A3], displacement [A1, NF1] and other drought impacts such as conflicts [A1, UW1, PW3] (Mach et al., 2019; Peters, 2021). Humanitarian stakeholders are interested in using groundwater data to triangulate and validate their existing early warning satellite and socio-economic indicators [PW3, UW3] (Gure, 2021). Humanitarian stakeholders also recommend studies quantifying the benefits of quality borehole construction instead of least-cost drill contracting [ND2], and they seek a cost-benefit analysis of boreholes versus water trucking for different livelihood zones and aquifers [ND5].

There are benefits to these stakeholders beyond research studies. Humanitarian decision making during droughts is “very much driven by personalities from a small group” [UA1] of academics, scientists and experts. In humanitarian forums, meetings and over social media, they can use groundwater information to better communicate the realities of water access on the ground and the emergency actions required [A2] at earlier stages of drought assessment and advocacy. Researchers can also form collaborations between high and low resource institutions to co-develop projects around groundwater datasets, developing in-country capacity to work with groundwater data and advancing the science [ND4].

6.3.1.3.4 Press

Public groundwater information availability can mitigate media speculation about water supply matters, which can misdiagnose the cause of water supply failures and spread misinformation to the public [PW4]. Accurate reporting can instead contribute to greater stakeholder accountability in WRM [PW4]. Journalists interested in climate change will also benefit from better quantification of changing drought and water availabilities [NW3].

6.3.1.3.5 Private Sector Industries

Monitoring holds economic value to industries where reliable water supply enables industrial processes to continue, whilst increasing the likelihood of securing further investment and improving public relations through good data reporting and working practices [PW4]. Development arms of multinational companies may also value monitoring technologies as an appropriate application of their technical expertise for non-profit objectives (NE2, ND4).

The benefits to all stakeholder groups are visualised in a thematic map (Figure 6.1), where the themes and sub-themes of groundwater data benefits are assigned to the benefitting stakeholder group(s) identified by the interviewee(s).

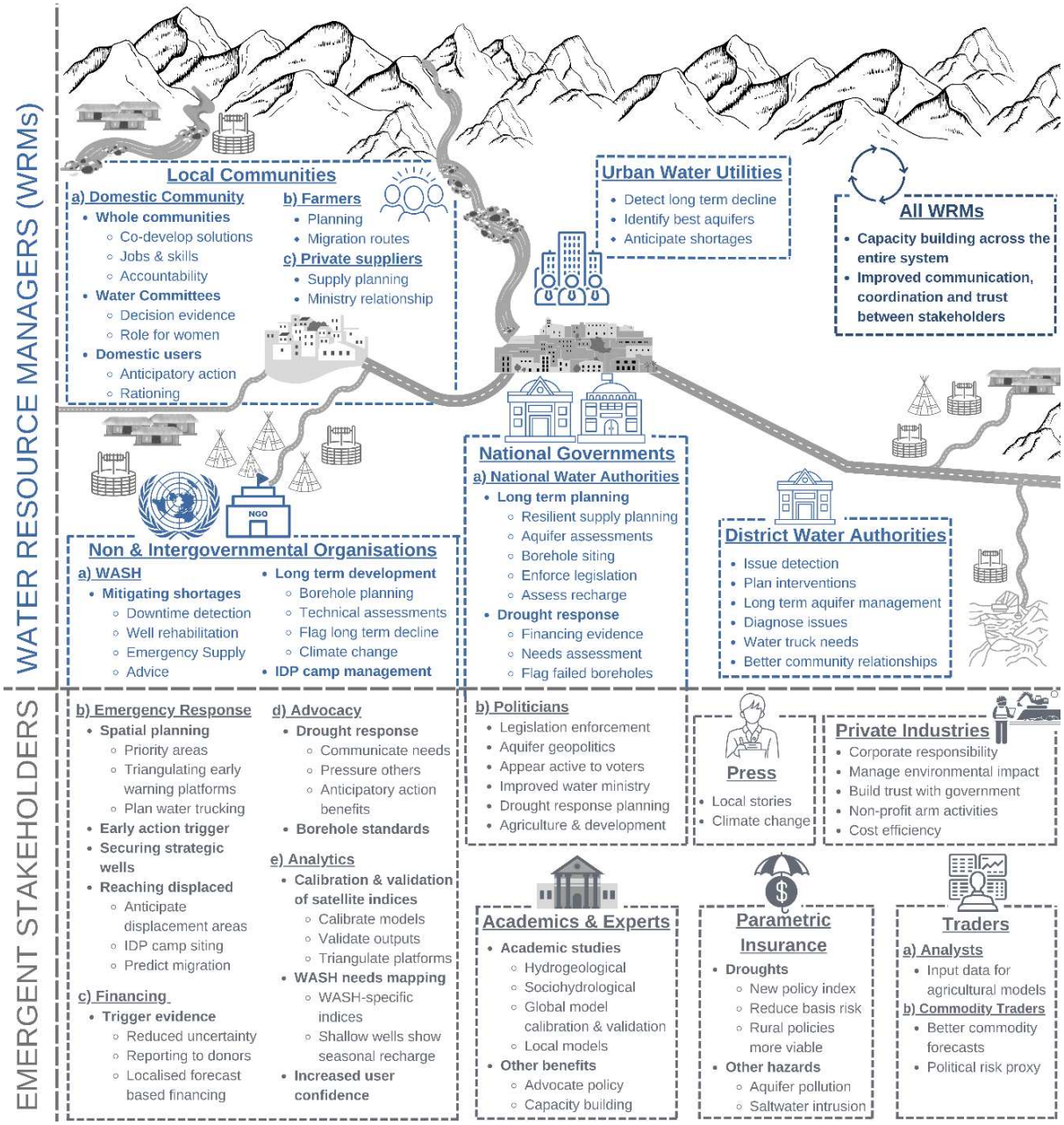


Figure 6.1. Thematic summary of the benefits of groundwater monitoring data for different stakeholders. Stakeholders are grouped as either Water Resource Managers (WRMs), the primary users of groundwater data, or emergent stakeholders – those with no prior experience of groundwater data who can benefit from analysed data. Background descriptions of these stakeholder groups are given in the methods (Chapter 2.3.3). Themes of benefits (bold) and sub-themes from thematic analysis are plotted for each of the 18 different stakeholder categories (underlined).

6.3.2 Discussion: Systemic Decentralisation of WRM

Better information for decision-making at the local level reduces community, local authority and private supplier dependencies on centralised NGO and national water authority assistance, thus unlocking their local capacity to develop a more resilient water supply independently (Figure 6.2; Foster et al., 2012; Scheihing et al., 2020). In this way, the national water authority diversifies from its active engineering role to also become a centre for data management, communication and coordination (Buytaert et al., 2014). The data should be pooled at the national level to ensure there is sufficient technical capacity and institutional support to generate and return advanced insights to local WRMs. Centralising data management is therefore a necessary step for decentralising WRM activities while technical skill shortages remain at the local and district scale (Chapter 3), though long-term operational networks should seek to develop increasingly polycentric and decentralised data management systems as local capacities improve (Buytaert et al., 2014).

If processed and communicated according to user information needs and levels of data literacy, advanced insights such as pumping rates, anomalies, models, forecasts, well efficiencies, aquifer parameters and qualitative advisory outputs can inform important local decisions (expert recommendations for groundwater data communication are outlined in the Supporting Information; Chapter 6.5.2). Local access to hydrological information enables a decentralisation of WRM decision making that harnesses the skills, interest, local expertise and innovation of locally based communities, WRMs and engineers. This sets a path away from criticised implementations of centralised WRM, where national authorities do not have the capacity, local knowledge or local presence to skilfully manage complex and distant local water supply networks (Buytaert et al., 2016; Zulkafli et al., 2017). To communicate these systemic differences brought by data-informed WRM, an interpretive conceptual model is presented that visually compares the current paradigms of WRM in the Horn of Africa, as described by interviewees, with their descriptions of decentralised systems of WRM. Their descriptions of decentralised WRM systems is prospective and predicated upon decentralised stakeholders having regular groundwater data access and financially supported capacities to take local actions (Figure 6.2).

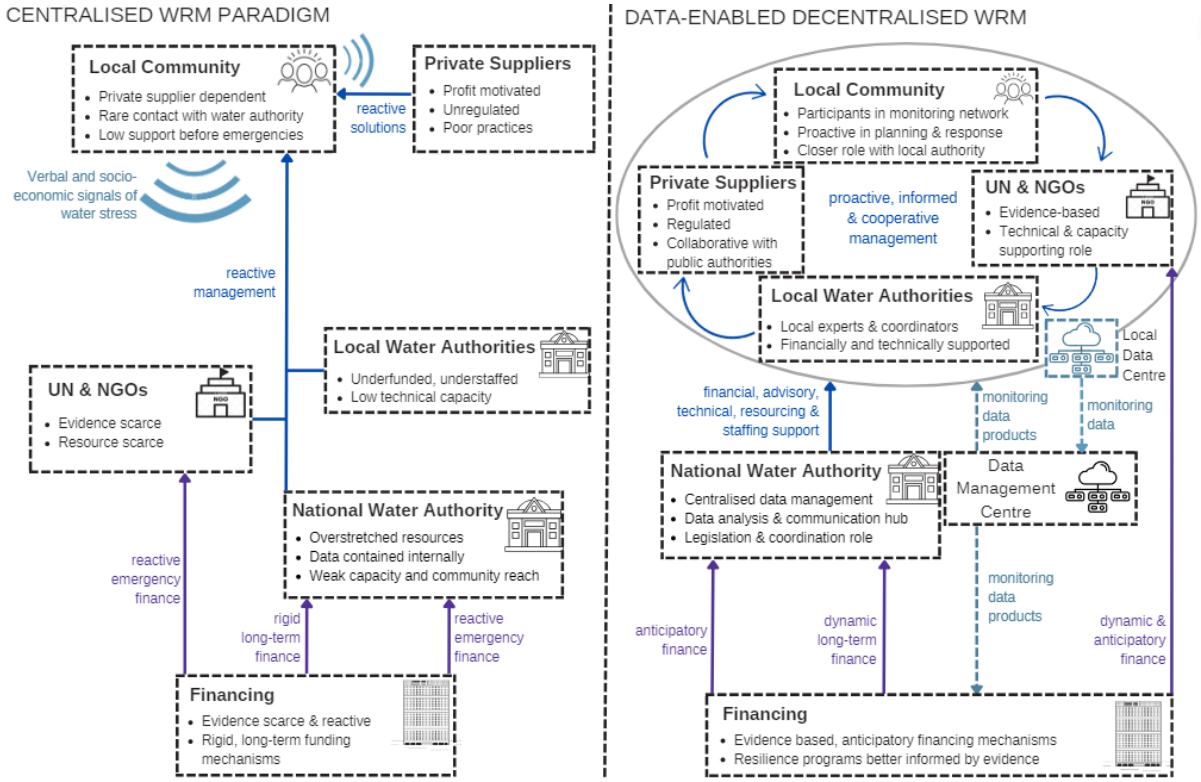


Figure 6.2. An interpretive conceptual model of the data-enabled transition from centralised WRM paradigms to decentralised WRM.

6.3.3 Implementation Challenges

Whilst all participants responded positively to the technical feasibility of upscaled monitoring systems, many stressed the importance of explicitly addressing implementation challenges if future implementations are to realise the data's potential value. The expert-perceived challenges for integrated groundwater monitoring systems have been thematically categorised (Figure 6.3).

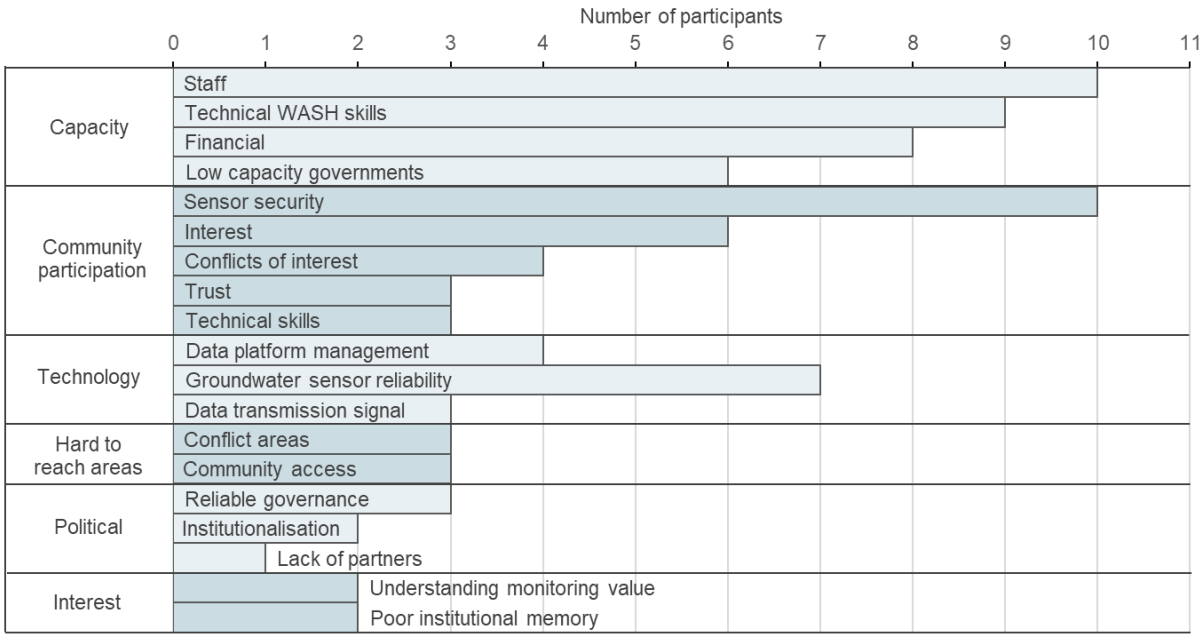


Figure 6.3. Thematic summary of expert-identified challenges for the setup of integrated groundwater monitoring systems.

The modal perceived challenge is generating the institutional capacity to setup, maintain and use the outputs from the monitoring system. A shortage of professional staff with low technical skills will be a barrier unless there is investment into staff, their capacity and improved technologies that alleviate their monitoring workload [UA1, UW3, MN2, MN1]. There are also financial challenges in funding monitoring sensors, employing full-time staff members to operate the monitoring system, and in the potential need to financially incentivise some community participants [A2, MN1, MN3, NE2, NF1, NF2, NW3, UW3].

"we're cautious all the time about the cost of operation and maintenance."

-MN1

Low technical WASH skills also cause "a lot of data literacy issues" [UA2], which can be a challenge for ensuring monitoring data is used. If a monitoring system fails to process, simplify and communicate monitoring outputs to users with lower data literacy, stakeholders will not use the monitoring information, its potential value will not be realised and demand for the monitoring system will decline [UA1, PW3, UW4].

Community participation in groundwater monitoring with automated sensors is sensitive and requires a commitment to ethical practices, citizen science and user-centred design (Zulkafli et

al., 2017). Without steps to inform, negotiate and make agreements with community participants, sensors are more likely to be vandalised [MN2, NA1, NA2, MD2] out of curiosity [UW1], lack of trust in their reasons for being there [MD2, PW3, UW1] or genuine conflicts of interest with stakeholders concerned about sensitive data becoming public knowledge and creating competition for water sources. Data access is therefore a fundament to be discussed and agreed prior to installation, with permissions likely to vary between stakeholders and communities [MN2, NA1, NA2, MD2]. The challenge of data literacy in communities equally requires capacity building for output information to be integrated into community decision making [MD5, MN3, NW3].

"are these things going to be destroyed right away? Have you created trust and interest in the community to let those [sensors] stay?"

-NA1

Many experts express concerns about existing automated technologies being unfit for purpose [MD2, MD3, ND5, NW2, NW3, NW4, PW3, UA2, UW1, UW2]. Pressure transducers are considered difficult to install, unreliable, difficult to collect and process data from, insufficient in battery life and can be difficult to connect by cable to automated data transmission units.

"you wonder, is it a help or a hindrance? These automatic divers that are so difficult to use, and people forget about them or move them or forget to collect the data. Or they run out of battery and you have to send them off for replacement."

-NW4

"if you have a sensor network that has quite a high maintenance overhead, as in, the units keep breaking down, it's expensive to get someone out there to sort them out and it's going to be kind of counterproductive."

-NW2

Innovative automated monitoring solutions are required to overcome the technology challenge, which can also alleviate the capacity challenges of staff, technical skills and cost if they are more reliable and able to send data to a platform that automatically processes the data [NE2, NW3, PW1, UW1] (Calderwood et al., 2020; Solinst, 2021).

Accessing hard-to-reach and conflict affected areas is a prohibitive localised challenge to groundwater monitoring [NA1, NA2, ND1, ND2, ND5, NF1]. However, historical and nearby groundwater datasets can be used to calibrate groundwater simulations in affected areas, offering modelled groundwater information to high-level programmers in times of conflict

[PW4, UA1] (Veness et al., 2022). Equally, prior experiences of monitoring may incentivise local monitoring for better self-management of scarce resources in conflict areas [ND2].

"in northern Tigray, Ethiopia, you don't have a chance… Like, the government's never gonna let you bring a bunch of sensors into Tigray."

-NA1

Low interest in groundwater monitoring is an outstanding challenge due to a lack of understanding of the data's value at high levels of decision making [UA1, UA2, MN1, NA1, NE1, UA2]. This includes politicians, who are in positions to institutionalise groundwater monitoring through legislation, licencing and policy [NE1, NF1, PW2, PW3, UC2]. Both humanitarian and government stakeholders have short institutional memories due to regular staff turnover and short-term funding periods, which has contributed to the discontinuation of previous monitoring projects [NE1, PW3]. Therefore, groundwater monitoring programs require local-national scale institutionalisation to be sustained long-term through future funding and political cycles [PW2, NE2].

6.3.4 Groundwater Monitoring Implementation Framework

This section completes an analysis of the thematically-coded expert recommendations for resolving monitoring system challenges, which have been interpretively organised into 5 chronological themes. The analysis culminates in the presentation of a conceptual 5-stage implementation framework for groundwater monitoring that summarises the key recommendations.

6.3.4.1 Stage 1 – Preparation & Procurement

At the start of groundwater monitoring programs, there is typically initial enthusiasm among funding and implementing partners to skip to Stage 2 and immediately install sensors in a pilot system [MD5, PW3, PW5]. However, careful procurement and setup is required to avert challenges from arising later that will compromise project momentum [PW3, PW5].

"what we see time and time again is that people undertake a groundwater monitoring campaign with no actual plan about the management, presentation and frequency of collection or upkeep for that data. So what happens? Monitoring occurs for a couple of years

and then everyone forgets about it. Why? Because they can't see the data. They can't use it if they can't see it, and then they wonder what the point of spending time and money on it is."

-PW5

Starting with procurement, sensor testing must be completed to ensure those chosen are reliable and connecting to selected telecommunications networks where possible [MD2, MD3, MD5, UW2]. Furthermore, fully operational data servers and an online platform should be setup and populated with historic groundwater data collected through census of all relevant WRMs [PW5]. The platform should also digitise relevant planning information such as geological maps, borehole drilling reports, historic pumping tests and community key informant contact information to assist with data interpretation and increase engagement with the platform [MD5, MN1, PW5].

"before we start everything else - we just need in Somaliland a full water point census to figure out where they all are and what the baseline water table level is across the country."

-PW5

Dedicated, full-time staff are needed to form a 'data management centre' at the national level, and district-level managers should be hired to coordinate management of local monitoring stations and data communication [PW3, PW5]. Field technicians with the skills to maintain sensors and communicate with hosting communities should also be resourced in project areas [PW3]. Initially, these staff bodies require partnership with external expert organisations to provide technology support, technical advice and continuous capacity building of the WRMs [UW2, ND4, MN2, A2]. This can be a consortium of partners across NGOs, the UN, the private sector and academic institutions to contribute respective expertise and improve institutional memory for the project [PW3, A2, MN2, ND4, NF2, NW3, UA1, UA2]. Non-profit partners are likely to be the source of project funding for the first years of the monitoring system before circular or alternative funding sources are secured at later stages [A2, ND4, NF2, NW4, PW2].

"you need information centres; you need small scale institutions that will champion monitoring. And that essentially means setting up work environments where you have got six or seven people working in smaller groups who are actively involved in quality assuring the integrity of data that's collected, entering it, and then making sure that the platform of data can fit into tools that people can use."

-PW3

Data sharing agreements should be in place with partners and communities hosting the pilot system [A2, NW3, NW5]. Interviewees stressed the importance of making data open access

where possible [A2, NW3, PW2, NW4, UA1], though the feasibility of fully open data access depends on the public sensitivity of the wells being monitored and stakeholder-agreed data permissions [MN1, NW3]. For example, government and utility owned well data can be fully open access in politically stable areas [A2, NW3, PW2], whilst privately owned sources will require some data privacy restrictions following consultation with hosting community stakeholders [MN1, NW3].

Local communities and WRMs are integral to the co-design of groundwater monitoring data outputs according to their information needs and data literacy [MD2, NF1, PW4, UC2, UW1 UW2, UW4] (Contzen et al., 2023; Smith et al., 2023; Twomlow et al., 2022; Zulkafli et al., 2017). Optimal outputs and design will vary between regions and stakeholder groups, so must remain adaptable during the remaining framework stages (Smith et al., 2023; Zulkafli et al., 2017). Participant recommendations from this study of how to present groundwater data to different stakeholder groups are outlined in the Supporting Information (Section 6.5.2).

6.3.4.2 Stage 2 – Pilot

A dense network in a pilot district is a better simulation of the final monitoring system than sparse coverage across a national scale [MN1, NW1, GO1, A3] (IGRAC, 2020). Each installation requires community and local authority consultations, data-sharing agreements, trainings and capacity building workshops to secure long-term participation and active engagement [UW2, A2] (Contzen et al., 2023). Community capacity building is a resource-intensive but essential systemic step for overcoming the challenges of groundwater monitoring (Figure 6.3) and unlocking the potential capacity of decentralised WRM stakeholders (Figure 6.2).

> *"without these trainings it is impossible to maintain monitoring because skilled local volunteers or paid workers are needed."*
>
> -UW2

"Strategic" boreholes are a priority for monitoring, as well as being the most accessible for monitoring as they are often operated by the government, UN or NGOs [MD1, MD3, UW2, ND3]. A borehole is considered strategic if it has a high supply volume and resilience to drought, meaning it becomes an "anchor" borehole in dry seasons when other nearby sources

fail [UW1, UW2, PW4]. Experts stressed the importance of securing the supply of these in drought to avert mass displacement and food insecurity [UW1, UW2, NE2].

"strategic boreholes, put the word in capitals and underline it - strategic boreholes!"

-UW1

"we cannot be only focused on the boreholes but also the major shallow wells"

-UW4

However, monitoring shallow wells and low volume boreholes is also important with many supplying 100s-1000s of people. These are a key early warning indicator of drought stress, since these shallow sources are frequently first to fail in drought [PW2, UW4] (Ford et al., 2022). Securing these water points is important for mitigating the initial displacements and lifestyle impacts that mark the onset of socio-economic drought [PW2, UW4, MD3, ND2, ND3 NW1, NW3, NW5, PW5, UA1, UC2, UW1, UW2, UW3, UW4]. Where long-term maintenance of monitoring in small community wells is too challenging or resource intensive, a short 1-year monitoring campaign can be sufficient for calibrating shallow well and borehole simulations in the monitoring system [UA1, UA2, PW4, PW5] (Veness et al., 2022).

For privately owned boreholes, the operational benefits of data visibility will often be a sufficient incentive to participate if terms of data privacy are satisfied [UW1, NW1, NW4]. However, some owners may require financial or legal incentives to cooperate depending on local interest and context [MN2, UW2, NW1, NW4]. The growing popularity of Public Private Partnerships (PPPs) over community management committee approaches in WRM provides case studies of private providers transparently sharing public groundwater updates in this way [A2, MD5, NW1, PW2, PW3] (Adams et al., 2019; Hashi et al., 2016; Hashi and Barun, 2019).

"we have these private companies and most of them do not have issues, because they also want to know this information. You know, they are curious to know how the water level is, how many hours were they pumping and how the drawdown is going. They're quite interested in knowing this information."

-UW1

In some areas, manual groundwater monitoring may fulfil information needs and be easier to collect than sensor-borne monitoring information [NW2, NW4, PW5] (Ford et al., 2022; Mao et al., 2020, Zulkafli et al., 2017). Regardless of location and method, it is important that monitoring programs document key informant, engineer and relevant community details to

ensure institutional memory of previous interactions between stakeholder groups [PW3].

6.3.4.3 Stage 3 – Expansion

Once a pilot has achieved genuine support and engagement with the data by the intended stakeholders, the model can be repeated in other districts. The co-design process should continue with local stakeholders to account for different local capacities and information needs [A2, NW3, PW2, NW4, UA1]. Community workshops and capacity building programs must also scale through training of local implementation partners in each new district [UW2, ND4, MN2, A2].

6.3.4.4 Stage 4 – Institutionalisation

Demonstrable benefits from monitoring will be persuasive evidence for political institutionalisation of the practice [MN1, PW5]. Positive value experienced at the local level will also increase support and compliance with legislation enforcing borehole monitoring and data reporting, which is an essential step for the institutionalised long-term maintenance of the system [MN1, PW5, MD5, NE1, PW4] (Foster et al., 2012).

"you absolutely need to have long-term monitoring and pumping tests become a mandated part of the borehole drilling process."

-PW5

Monitoring legislation should be introduced concurrently with formal drilling, borehole ownership and drilling supervision licences for those that comply with government standards [MN1, PW5]. The availability of monitoring data improves the feasibility of regulating and enforcing these standards [MN1]. This promotes professionalisation among decentralised WRMs, but it will require substantial financing to raise awareness of the policy change, provide training to licenced professionals and subsequently enforce the new laws [PW4].

"until the water authority has that power and has the resources to enforce [drilling standards and borehole supervision], or, if necessary, deploy its own supervision staff, nothing's going to change."

-PW4

Depending on the financial capacity of the government and partner stakeholders, the monitoring can either continue to be funded by internal and donor funding, or 'circular funding' options can be considered, whereby revenue is generated by data productisation and reinvested into the monitoring system [PW4, PW5].

"users would reasonably be expected to pay something for access to your data, which doesn't seem unfair, because keeping a database going costs money"

-PW4

A range of emerging stakeholders can gain significant value from groundwater monitoring data, to the extent that they would be willing to pay for access [PW4, PW5, A2, ND4, NF2, NW4, PW2] (Figure 6.1). Free, user-tailored access and communication must be maintained for founding WRM partners and communities. Furthermore, non-sensitive public groundwater information should remain open access [A2, NW3, PW2, NW4, UA1]. However, there is a clear and substantial revenue-generating potential in creating value-added, inter-operable hydrometric data products from insensitive or aggregated elements of the wider groundwater data suite [NA2, NE1, NF1, MD4]. This can be through simple fee-for-data services to users such as academics, NGO/UN analytics teams and private borehole drilling contractors, or through major financial players such as parametric insurance providers and commodity analysts that may invest in partnerships and access tailored data products [NA2, NE1, NF1]. The economics, ethics, potential externalities and appropriate structuring of productising and selling groundwater data all require further research and review, as these datasets will become a tempting revenue stream for its gatekeepers as the volume of data grows. An awareness of its economic value can help to ensure that it does not become corrupted and fraudulently sold, whilst also creating opportunity to negotiate among partners and develop new circular-funding arrangements. These partnerships can harness both the economic potential value and the social value of providing data products to emerging stakeholders [PW4, A2, NF2].

6.3.4.5 Stage 5 – Operational System

"It is important in the long term that the government then takes control of this system and their monitoring database too, so we are just the partners that are helping them to get setup with this process."

-UW2

Given the need for advanced skills capacities to maintain sensor technologies, coordinate monitoring networks and the generate advanced insights from data, the modal recommendation is long-term government water authority ownership of the data and monitoring system [A2, MD2, MN1, NA2, ND4, NE2, NW1, PW1, PW2, UW2, UW3]. This reflects the transition of the central water authority's role from the practical completion of water engineering projects to a higher-level managing and coordinating body (Figure 5.4). Therefore, where monitored sources are privately or community-owned, these sources require data sharing agreements in a public-private partnership model specifying privacy and data access [NW1, NW4, A2, MD5, PW2]. In areas with weak government reach or capacity, non- or inter-governmental organisations can be initial providers of monitoring system governance before handing over to national or district governments once capacity and authority are established [PW3] (SWALIM, 2023).

This requires sufficient capacity in the receiving entity [UW2, PW3]. Private partners may remain necessary for technical support through the management of sensors and data, and they may assist with productisation and revenue-generation from the data if that funding pathway is chosen [MN1, PW3].

Continuing communication between central government, district and community partners remains essential to avoid monitoring system failure due to a lack of locally observed benefits and a loss of local stakeholder support for data collection [PW3, NW2, UW2]. Maintaining this communication is also key to unlocking the capacity of decentralised WRMs (Figure 6.2). To ensure this, the monitoring system should complete annual reviews to continue optimising its setup and to ensure the data continues to be useful to its intended users (Maxwell et al., 2021).

"If [local stakeholders] are not seeing those benefits, then that voluntary motivation could erode over time."

-NW2

Participants stressed the need for substantial concurrent investment into the financial, technical and staffing capacities of government water authorities to make groundwater monitoring systems useful [A2, MN1, MN2, MN3, NA2, NE2, NF1, NF2, NW3, PW3, UA1, UA2, UC1, UW2, UW3, UW4]. Many evidence-based actions taken by WRMs would be resource and staff intensive, so there must be the capacity in place to proactively act upon data evidence.

"It doesn't matter if the government has all the information in the world if they only have one staff member, no money, and maybe no understanding of how to actually do anything with the data."

-UA1

"we need capacity building of the team so that we can actually be able to take advantage over the data and take decisions when it is made available."

-MN1

"there's currently a massive underinvestment in what's required to facilitate this transition and make it successful."

-PW2

These expert recommendations are presented in a 5-stage conceptual implementation framework for the setup and governance of integrated groundwater monitoring and decision-making systems (Figure 6.4). The framework presents the individual recommendation codes from the thematic analysis analysed in this section, and it interpretively organises them into a 5-stage chronological sequence until an indefinite operational system is reached in Stage 5.

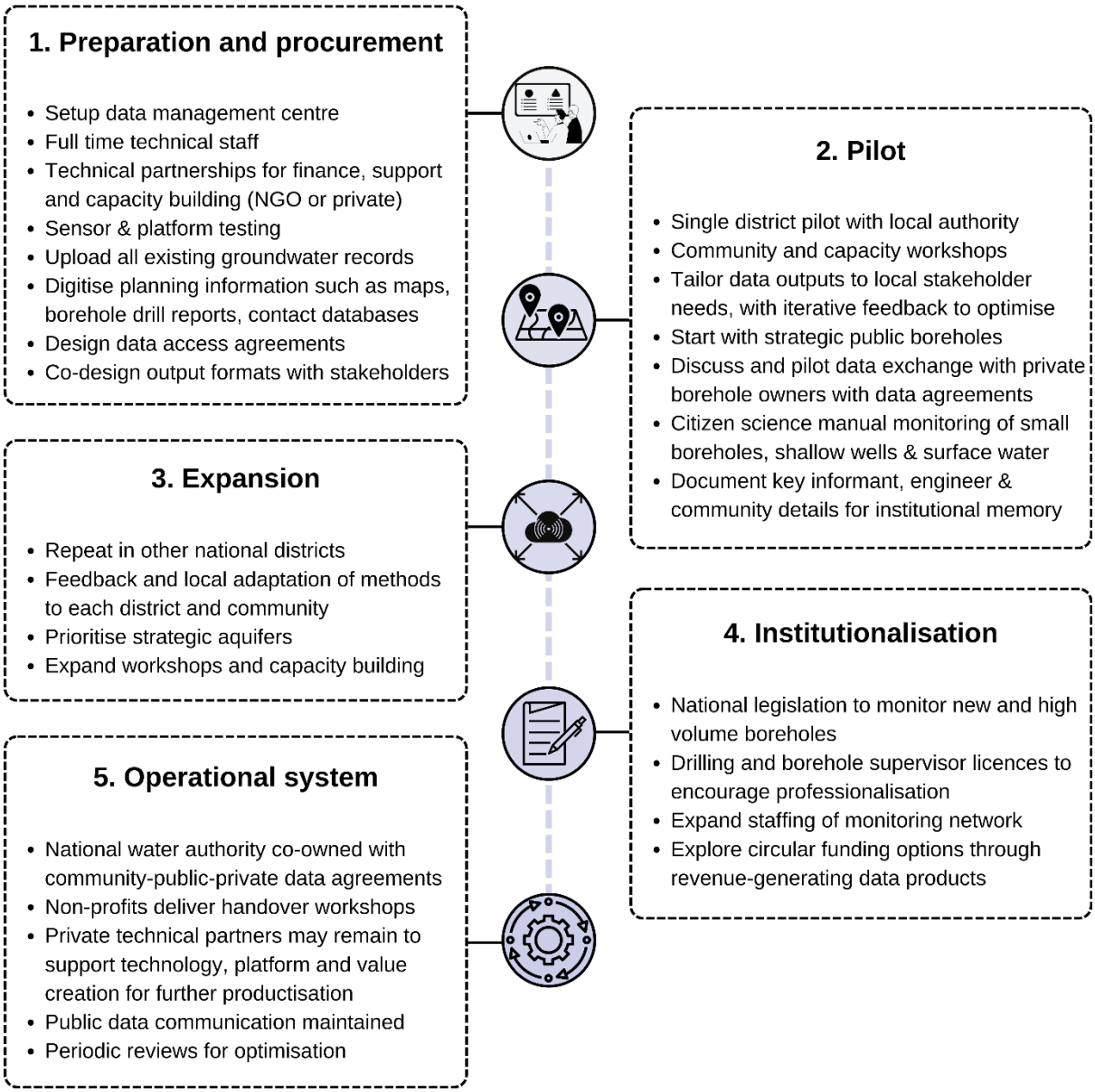


Figure 6.4. Expert-guided implementation framework for setting up integrated groundwater monitoring and decision-making systems in resource-scarce contexts. The bullet points represent individual recommendation codes from the thematic analysis of responses to interview Questions 10 – 12 (Chapter 2), whilst the codes are interpretively organised into an approximately chronological 5-stage sequence. Whilst these are pragmatically presented as a sequence, some stage transitions may be concurrent, iterative or cyclical in practice.

6.4 Conclusions

An inductive assessment of groundwater monitoring data's potential applications and beneficiaries identifies substantial benefits for 18 different stakeholder groups (Figure 6.1). For Water Resource Managers (WRMs), the primary users of groundwater data, groundwater

information can support a systemic change to decision-making that evolves management towards more evidence-based, proactive and decentralised methods (Figure 6.2). Experts also identify system-wide benefits for WRMs through greater capacity building, communication and co-ordination of management activities. Emergent stakeholders with no prior experience of groundwater data may be able to use monitoring information as an evidence-base for aid financing and numerous other applications, if it can be processed and communicated to their information needs and levels of data literacy.

The major challenges to the setup of monitoring systems are technology, capacity and community participation (Figure 6.3). Continuing to improve user-friendly groundwater monitoring sensors for automated data collection, transmission and processing has the potential to significantly alleviate monitoring implementation challenges. However, this must also be supported by concurrent investment in the financial and technical capacities of authorities, communities and partner WRMs to ensure they can take scaled, evidence-based actions upon groundwater data. Overcoming these challenges requires cross-disciplinary partnerships to support water authorities, drawing together experts in the relevant political, humanitarian, economic, social and technical fields.

A 5-stage, expert-guided implementation framework organises expert recommendations for setting up sustainable groundwater monitoring and decision-making systems that realise the data's potential value to users (Figure 6.4). Thorough preparation, procurement (Stage 1) and piloting (Stage 2) can ensure sufficient monitoring infrastructure, institutional capacity and stakeholder co-design are developed before expansion (Stage 3). Skipping these first two stages has been a persistent cause of monitoring system failures in Sub-Saharan Africa previously (Adelana, 2009; Foster et al., 2012; IGRAC, 2020; Maxwell et al., 2021; Pavelic et al., 2012; World Bank, 2020). Institutionalisation (Stage 4) for long-term maintenance of groundwater monitoring can be achieved through legislation and professional licencing to make groundwater monitoring mandatory. Equally, long-term funding may be secured for the system through the sale of value-added groundwater data products or by securing long-term grant funding. Governments, communities and local partners will be able to take responsibility and ownership for the operational monitoring and data system (Stage 5) if there is a commitment to capacity building by partner stakeholders throughout the first 4 stages.

By assessing the benefits and outstanding challenges of groundwater monitoring, this paper advances the evidence basis for decisions regarding its investment. By constructing an

implementation framework, it provides a pragmatic guide for the setup of these systems once programs are funded. Unbiased appraisals of groundwater monitoring programs are uncommon, but it is important that the next generation of monitoring systems are continuously evaluated to both optimise those systems and generate case-studies that elucidate their value and attract further investment.

The qualitative scoping in this study can instigate two streams of further research. First, the qualitative scoping of users and beneficiaries is an important pre-requisite step before quantitative valuations (Kumar et al., 2010). Therefore, now that the users, applications and benefits of groundwater data have been scoped in the Horn of Africa's context, deductive quantitative valuations for these users can be completed to further elucidate the value of groundwater data to potential investors or donors. Second, valuations and clear implementation pathways are absent for most hydrological variables and contexts, but they are needed to provide a better cost-benefit basis for their investment. Therefore, the simple qualitative approach demonstrated in this study can be replicated for other variables and situational contexts to fill this knowledge gap. Valuation is fundamental to investment (Garrick et al., 2017), and hydrological data needs much clearer value propositions and pathways to implementation if it is to attract greater interest from potential investors or donors.

6.5 Supporting Information

6.5.1 Recommended Groundwater Data Presentation

User-centred design is an important but frequently neglected step in the setup of monitoring and communication networks (Maxwell et al., 2021; Zulkafli et al., 2017). For information to be useful to users, systems must provide the desired data in an interpretable and engaging format at the correct spatial resolution and frequency (Twomlow et al., 2022). Participants in this study made recommendations for groundwater data presentation (Figure 6.5).

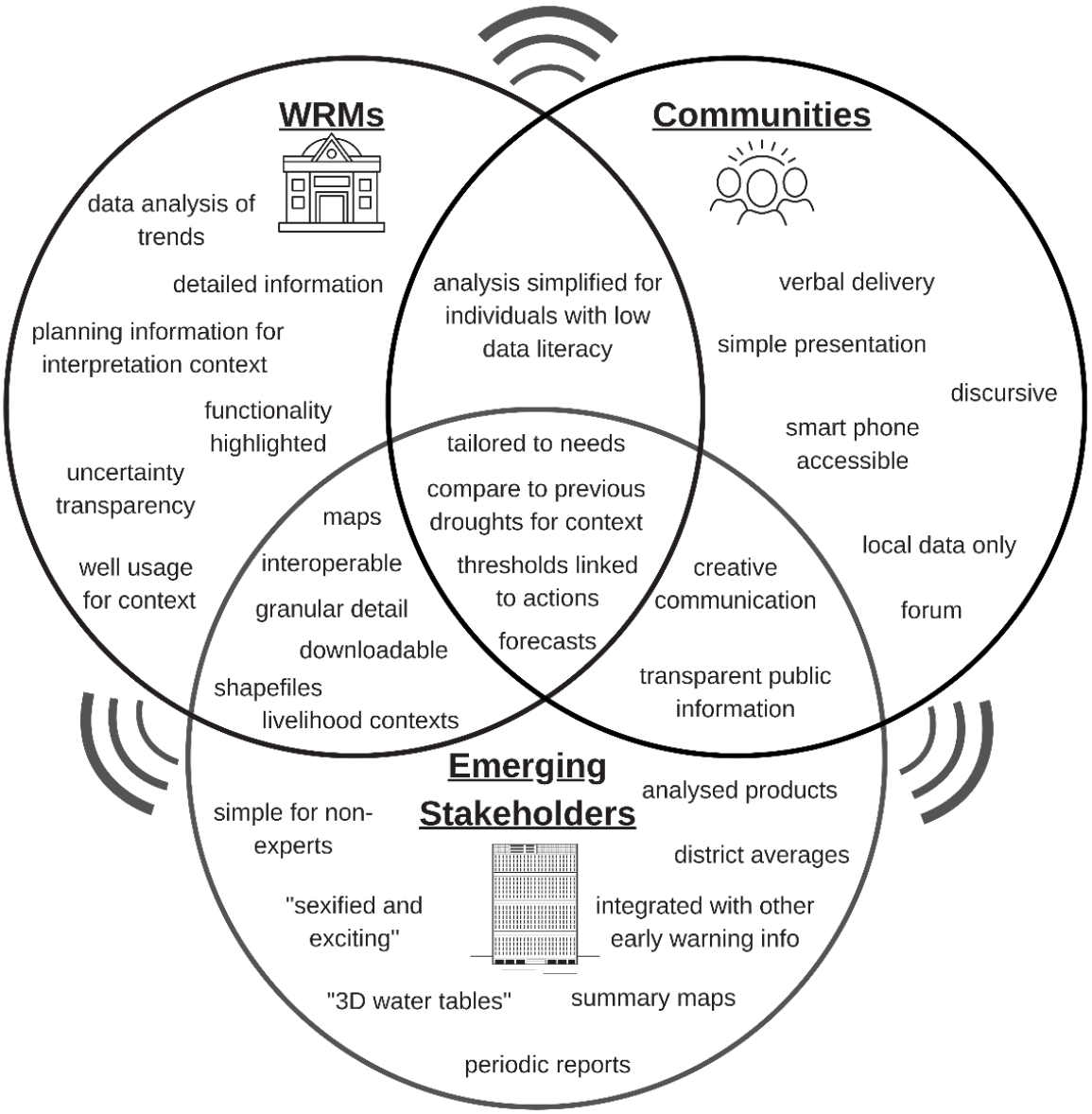


Figure 6.5. Expert recommendations for groundwater data presentation, thematically coded to the relevant stakeholder group.

The modal suggestion is for groundwater levels to be contextualised with historical data, so water levels can be presented as anomalies and be directly compared to water levels during previous drought events [NA1, NE1, NE2, NF1, PW5, UA2, UC1]. This simple contextualising information transforms a raw groundwater level reading into an understanding of its local and regional socio-economic impacts. Although each drought has unique factors modifying the event, comparison of water levels to previous droughts enables a 1st order comprehension of the severity [NF1, UC1]. A lack of long groundwater time-series is a challenge to providing this; however, short time-series of groundwater level readings can be used to calibrate borehole simulations of water levels over previous decades to generate this comparison (Veness et al., 2022).

"we get a lot of questions of how's the current situation compared to 2011 or 2017, which were the last big drought emergencies [in East Africa]. And so, in any of these maps, you should be able to pick those years and compare."

-UC1

"But we need more than just, oh, the water level's low. We need to know if it's historically low when compared to 2010, in the lead up to a famine, or, if it's historically low compared to 2016 - 2017. Well, we know that was, you know, one of the worst droughts ever, right? Like, that little bit of synthesis of the information, even within a dashboard is like, incredibly useful, I think, to us."

-NA1

Thresholds for action can be defined for different stakeholders and communicated alongside groundwater data. This "combines groundwater data with the common analytical frameworks" [NA1], where typically a range of monitoring indicators are used by governments and humanitarian agencies with thresholds beyond which pre-defined actions are triggered. By clearly displaying the data relative to the threshold-levels for triggering action, the data becomes more actionable [NF1]. For WRMs and communities, the interpretation of the data will often need to be more detailed and granular, therefore requiring full data access for more detailed planning than simple thresholding [UA1].

WRMs require full detail data access as well as simplified pre-analysed groundwater data outputs, accounting for the range of data literacy in these institutions and the complexity of the decision-making required [NF1]. However, a groundwater information system should also contain supplementary planning information to contextualise the quantitative water level,

quality and pumping data with qualitative groundwater data [NA1]. The well's function, historic engineering reports and the livelihoods of those accessing the water adds decision-making value to the groundwater data by framing it in the context of the users. For example, water quality can be maintained at a higher threshold if the well is known to be used for drinking, or, a borehole's functionality can be prioritised if it is the anchor domestic drinking source in the local district [NA1, UA1].

"in which livelihood zones is this shortage occurring? And is this occurring in areas where you know water levels are important, and may be a tipping factor as they are in agro-pastoralist areas where, if you lose water supply, your goats can't get to the next water point along and you're looking at a collapse of the market?"

-NA1

Qualitative, contextualising information on livelihoods and their vulnerability to groundwater shortages is also important for emerging stakeholders, whose lack of groundwater expertise risks misinterpretations of raw data [UC2, UW4]. It is better therefore to provide pre-analysed groundwater data outputs, where pre-analysed figures are explained by an expert using simple terminology [UW4, NF1]. Periodic reports and data outputs on a weekly or monthly basis are useful, given the longer temporal gap between high-level decision-making among emerging stakeholders [NF1]. These outputs should be interoperable with other hydrological data, integrated with existing monitoring and early warning systems, and presented in an attractive style that will increase engagement by potential users [UA2, NA1].

For community WASH committees, private engineers and domestic users, effective communication of data analysis insights can be useful for highlighting invisible threats such as declining borehole efficiencies and water qualities [PW3]. It can also help diagnose the cause of borehole failures when causes are complex [PW3, PW4, NW2]. Where there is low data literacy, findings need to be explained verbally or through simple data presentation and basic explanation of findings [MD2]. Data literacy and usage of smart phones are increasing across Sub-Saharan Africa (IGRAC, 2020; World Bank, 2022a), so for many, online platforms and smart phone applications can be an effective tool for a 2-way transfer of monitoring information, data insights and discussion. Communities must be regularly engaged as central participants in monitoring and linked decision-making systems through regular forum between stakeholders, where information, ideas and solutions can be shared [UW1].

7 Discussion

7.1 Overview

Prior to the conclusion (Chapter 8), which sets out academic contributions and a research outlook, this chapter draws together the findings to discuss their relative contributions to the overarching issue of resolving data scarcity in WRM (Chapter 7.2). It then hosts a discussion of the study limitations, the subsequent confidence in my findings, and the generalisability of those findings to evaluate the validity and strength of the respective chapter conclusions (Chapter 7.3). Chapter 7.4 then extends the discussion of attracting investment towards water monitoring, exemplifying the need for innovation and rebranding to attract investors once a clearer investment and feasibility basis has been established.

7.2 Towards Resolving Data Scarcity in WRM

Each of the chapters address different knowledge gaps across the theme of resolving data scarcity issues in WRM. Chapter 3 first contextualises the problem of data scarcity using the case study WRM and drought in the Horn of Africa. By initially establishing barriers to drought management, the chapter exemplifies the impacts of data scarcity and its inter-relationships with other drought management barriers in the Horn of Africa. By then establishing stakeholder information needs in drought and water resources management, Chapter 3 also elucidates the potential role of hydrological data in the humanitarian management of droughts. Its mapping of water monitoring information needs sets up Chapters 5 and 6, which assess the practical viability of meeting groundwater data information needs in the Horn of Africa and the benefits of groundwater data to those stakeholders. Although Chapter 4 principally focusses on the re-conceptualisation of the drought DRM paradigm framework, its emphasis on shifting operational frameworks towards ex-ante drought management also highlights the importance of hydrological data in enabling ex-ante management mechanisms. Chapters 3 – 6 therefore all

serve to elucidate the benefits of water monitoring data to advance its investment basis, and Chapters 5 – 6 further advance the feasibility basis of monitoring through improved technical and operational methods of setting up groundwater monitoring systems.

Given the broadness of the theme, the chapters as a collective do not fully 'resolve' all the knowledge gaps related to data scarcity in WRM. For example, the sole focus of Chapters 5 and 6 on groundwater data omits other hydrological variables, and the regional focus on Somaliland, Somalia and the Horn of Africa does not capture drought processes in other global regions similarly suffering from data scarcity. However, in taking the case of the Horn of Africa, where the nexus of issues in groundwater, drought and WRM are especially acute, the research targets priority issues relevant to data scarcity and has findings that have relevance for WRM and drought DRM internationally (Chapter 7.3). The chapters also aim to instigate further research into the theme with their respective contributions. For example, Chapter 5 invites adaptation of the groundwater model and data presentation to local contexts, and Chapter 6 provides a methodological template for further qualitative research into the value of other hydrological variables and situational contexts. The full list of identified research topics to build upon the findings of this research are detailed in Chapter 8.

7.3 Limitations, Confidence and Generalisability of Findings

The limitations of the semi-structured interviews (Chapter 7.3.1), quantitative methods (Chapter 7.3.2) and the extent to which they effect the confidence of respective findings are discussed here. The generalisability of the findings considering the spatial scope of the data collection (Chapter 1.2) is also discussed (Chapter 7.3.3). Given the range of limitations and the varying generalisability of the findings across the chapters, the inclusion of this discussion aims to support the reader in their own interpretations of their confidence in the findings, conclusions and the extent to which they can be generalised.

7.3.1 Qualitative Methods

The semi-structured interviews (Chapters 3, 4 and 6) had limitations in their sampling, interview methods, data presentation and results validation.

For interview sampling, capturing a representative set of interviewees for analysing complex multi-stakeholder, multi-scale drought and water resource management systems was a challenge. The scale of the systems meant that it was not possible to represent all positions across all stakeholder groups, so it was a practical decision to prioritise experts above a minimum level of experience who could account for their own roles and those of their colleagues during the interviews (Gumucio et al., 2021; Mach et al., 2019). In the 42-expert sample, stakeholders in academic and regional roles are over-represented compared to local stakeholders, and it is a further limitation of the regional system-scale analysis that local stakeholders were mostly sourced from Maroodi Jeex, Somaliland, with only 1 district level stakeholder from ASALs in each of Ethiopia, Uganda and Kenya. Not all major institutional groups are captured in the Horn of Africa region either, such as some government ministries or meteorological organisations. Sampling was limited by access, time, funding and difficulties of engaging expert stakeholders during the humanitarian disaster that followed drought during 2022-2023 (Chapter 2.2; OCHA, 2021a; UNHCR, 2021). To reduce representation gaps, stakeholders were encouraged to discuss the roles of other stakeholders in their interviews (Chapter 2), and the later sampling was targeted to ensure that most of the stakeholders previously identified as being important were represented. The number of new codes arising during the qualitative coding of each interview was tracked in NVivo as an indicator of when to complete interview sampling, which was at the stage when the amount of information arising from interviews became relatively low (Galletta, 2013; Saldana, 2021).

One limitation of the interview method related to the diversity of backgrounds among the participants interviewed. There was a need to simplify or situationally rephrase questions to stakeholders of different job roles, educational backgrounds or language capabilities, risking the introduction of interviewer bias in the responses (Galletta, 2013; O'Keeffe et al., 2016). The frequency of this was reduced by designing a simple interview template with open questions that were relevant and comprehensible by different stakeholder groups. A further limitation was the choice to conduct different interview sections for Chapters 3 and 6 during the same interview, which risked a bias in the results from the second part of the interview towards themes discussed in the first part of the interview. This was partly mitigated by significantly shifting the topic of questioning in the second part towards groundwater monitoring issues to avert significant overlap in the answers.

Whilst the data presentation of thematic plots to show the codes, themes and sub-themes from the thematic analysis are straightforward representations of the analysis results, the conceptual diagrams presented in the discussions of Chapter 3, 4 and 6 are more subject to bias in their design (Chapter 2.3.5; Patton, 2015; Mills et al., 2006; Saunders et al., 2015). The design of the conceptual diagrams represents my interpretations of the interview findings, but bias may be sourced from my pre-conceptions on the topic and my subjective interpretations of the interview data and its meanings. To avert these biases, the diagrams were iteratively discussed with colleagues familiar with my research during their design. All conceptual diagrams also received general feedback following their initial design from one of the expert participants (Thomas, 2016). This is less robust than a validation of the findings through feedback from multiple participants, however, repeat contact with the majority was difficult given their expert roles and their ongoing involvement in the Horn of Africa drought (Chapter 2.2). More participants are now being contacted for feedback as these chapters are prepared for academic publications, and the chapters will subsequently undergo a further academic peer review process prior to publication.

Despite facing these limitations, the methods followed common procedures of semi-structured interview and qualitative analysis (Chapter 2), and the research chapters reach conclusions supported by evidence from an expert stakeholder sample representative of most major stakeholder groups in WRM and DRM in the Horn of Africa. Whilst there is greater subjectivity in the weakly validated conceptual models (Thomas, 2016), these are transparently presented as being conceptual in the discussion sections of the chapters and they are closely derived from interpretations of the interview data in their design.

7.3.2 Quantitative Methods

The discussion and conclusions of Chapter 5 discuss uncertainty explicitly in challenging a paradigm in academic literature of favouring hydrological modelling confidence over practical viability in resource-scarce contexts (Beven, 2001; Mackay et al., 2014; Nature Sustainability, 2021). The limitations and uncertainties are therefore transparent in its methods. There is input uncertainty from the TAMSAT rainfall data, calibration uncertainty from equifinality, uncertainties in the lumped model design due to unrepresented physical processes, uncertainty in the short validation approach, and the study is only completed on 3 wells. However, in discussing the trade-offs between practical utility and modelling uncertainties, the conclusions

invite those adopting the method in practice to establish acceptable uncertainty thresholds that are specific to the local decisions that the modelling is being used to inform (Maxwell et al., 2021; Zulkafli et al., 2017).

7.3.3 Generalisability

In its focus on the ASALs of the Horn of Africa, especially the neighbouring ASALs of Somalia, Somaliland, eastern Ethiopia, northern Kenya and northern Uganda, the study captures a cross-border region with similar rural and urban livelihoods, climates, infrastructures, levels of governance, and issues of WRM (Chapter 1.2; Bjornlund et al., 2020; Hughes, 2019; Thomas et al., 2020; UNESCO, 2021; UN-Water, 2022). There are limitations in generalising this specific region, such as an under-representation of frequent conflict zones, political differences, local differences in livelihood vulnerabilities and areas of more acute water scarcity (Krampe et al., 2020). However, the similarities (discussed in Chapter 1.2) are appropriate for collective consideration in a systems-analysis that needs to be regional scale to fully capture important humanitarian stakeholders that operate at the regional level. A consideration of intra-regional differences and nuances is also maintained throughout the interviews and analyses, and elements of discussion in each of Chapters 3 – 6 raise the importance of localising the qualitative and quantitative approaches that build on the methods of this study in future research and practice.

The generalisability of the findings beyond the data collection area of Somaliland and the Horn of Africa ASALs (Chapter 1.2) is variable depending on the specific finding (Polit and Beck, 2010). Specifically, the generalisability depends on the contextual similarity of the phenomenon between the study region and other regions (Larsson, 2009; Lincoln and Guba, 1999). Issues of barriers and information needs in drought management are particularly context-specific, modified by significant differences in local climates, populations, livelihoods, infrastructure, stakeholders and governance systems. As such, Chapter 3 makes its conclusions for the Horn of Africa specifically, with the ASALs within the Horn of Africa the subject of most of the discussion and analysis as the most vulnerable regions with the most acute management challenges (Chapter 1.2). However, given the humanitarian target audience and the international remits of major humanitarian stakeholders in NGOs, the UN and the private sector, the findings in the Horn of Africa will have some familiarity and relevance for stakeholders operating internationally, especially in ASALs of low- and middle-income

countries (Larsson, 2009). Chapter 6, like Chapter 3, presents the results and conclusions from the interviews as a case study of the Horn of Africa. However, its focus on groundwater monitoring data scarcity is a theme that is similarly shared across ASALs of low- and middle-income countries internationally. The chapter makes clear that valuations and benefit scoping will be context specific, and it encourages the application of similar methods in different situational contexts to generate local investment bases for groundwater monitoring.

Chapter 4, in contrast, makes conclusions on drought management themes for countries internationally, due to the inclusion of internationally-focussed literature in its commentary-style narrative review. Interview data from the Horn of Africa and groundwater data from Maroodi Jeex, Somaliland are used as a collective case study to evaluate traditional and emerging drought DRM concepts. The interview data from one case study is in this case is considered sufficient to demonstrate practical issues in applicability of existing drought DRM concepts and the practical advantages of emerging concepts (Larsson, 2009). The proposal of an updated drought management framework deliberately includes terms that are adaptable to different local contexts, and the discussions within the chapter encourage the further adaptation of the proposed framework to local contexts.

Chapter 5 demonstrates a method that is applicable to other well sizes, climates, hydrogeological settings, and it invites adaptations of its methods according to local context.

7.4 Attracting Water Monitoring Investments

Chapters 3 – 5 each state a policy recommendation for greater investment in local hydrological data in their conclusions. Chapter 6 then advances the investment basis for groundwater data through a scoping of stakeholder benefits and an assessment of expert recommendations for practical implementation. Providing an improved investment basis is critical to attracting investment towards hydrological data collection, however, concurrent efforts to rebrand and communicate the value of these data is also necessary to engage potential investing stakeholders (UNESCO, 2022; UN-Water, 2023).

In Chapter 6, WRM stakeholders noted that hydrological monitoring does not have a reputation that excites investors or donors. Perceptions of the practice have been eroded by the technical challenges of collecting the data, the unclarified value of the data, a history of poor

communication of data insights, and a longer history of failed attempted monitoring projects (Foster et al., 2012; IGRAC, 2020; Pavelic et al., 2012; Sarni et al., 2018; World Bank, 2020; Adelana, 2009). In the food security and humanitarian sectors, there are comparable examples of data services with contemporary branding that have achieved substantial investment and engagement, such as The Humanitarian Data Exchange (HDX), the Famine Early Warning Systems Network (FEWS NET), and privately-owned Gro Intelligence (Chapter 3). For water monitoring systems, input from communication experts can help to establish how they can similarly reimage the practice to appeal to potential investors and users. The development and promotion of monitoring systems can be catalysed by championing organisations or consortia (Chapter 6.2.4.1). Such organisations will need specialist expertise in both the sociological and technical elements of water monitoring systems for them to support the range of implementing stakeholders with expert capacity (Bosco, 2006; Cressman, 2009; Krige, 2001; Law, 1992; Law et al., 2012).

Investments in hydrological monitoring systems should be matched with parallel investments in resolving the implementation challenges identified in the thematic analysis (Chapter 6; Maxwell et al., 2021; UN-Water, 2021b). Monitoring technologies, despite their potential to significantly reduce the challenges of hydrological monitoring, still suffer from high costs, unreliability and issues of power and telecommunication despite advancements in low-cost sensor networks and IoT (Chapter 6). Continued innovation in environmental sensors can improve existing technologies for purpose in low- and middle-income countries. There is equally a need for concurrent investment in WRM institutional capacities so that they can effectively govern water monitoring systems and have sufficient capacities to act upon information provided by hydrological data (Chapter 6). Attracting investment in institutional capacities also requires more regular valuations (Garrick et al., 2017). As such, there is also potential for hydrological monitoring data to generate evidence to support value propositions for investing in long-term institutional capacities (Chapter 6).

8 Conclusions and Outlook

The first findings presented in this thesis identified water monitoring data scarcity to be one of the leading barriers in the disaster risk management (DRM) of droughts in the Horn of Africa (Chapter 3), exemplifying the humanitarian consequences of reactive, information scarce systems of water resources management (WRM). The proceeding findings have then addressed key knowledge gaps relevant to the objective of resolving data scarcity and associated issues of WRM and drought DRM. The findings advance our understanding of the potential benefits and applications of water monitoring data, as well as our understanding of how data scarcity can be resolved in practice. Here, the individual academic contributions of the chapters are synthesised (Chapter 8.1) and their collective contribution towards resolving data scarcity in WRM is reviewed (Chapter 8.2). The thesis then concludes by outlining the outstanding research needs to further develop the research findings (Chapter 8.3).

8.1 Academic Contributions

8.1.1 Chapter 3 – Proactive Drought Management Needs Water Security Data

After contextualising the issue of data scarcity as one of the leading barriers to drought DRM in the Horn of Africa (Objective 1), Chapter 3 responds to calls for humanitarian information systems to be more user-centred in their design, by assessing the respective information needs of expert stakeholders in drought management (Objective 2; Maxwell et al., 2021; Zulkafli et al., 2017). It found that over 75% of its expert interview participants perceive unmet water security information needs for improved drought DRM, identifying potential applications for the data that fall into two major themes. First, WRM stakeholders can use higher-resolution datasets of water availability, access and use to inform their long-term planning of more resilient water supply systems, as well as the shorter-term, rapid detection of water insecurity risk to guide anticipatory actions. Second, humanitarian financing stakeholders described the

potential for processed water security data to improve the confidence of value propositions for financing WRM and humanitarian anticipatory action projects. The chapter is novel in its inductive assessment of drought DRM stakeholder information needs at the system-level (Objective 2), and the finding that local water security datasets can support ex-ante mechanisms of humanitarian financing has important actionable implications for stakeholders in coordinating and financing roles.

8.1.2 Chapter 4 – Updating the Drought Management Framework

Chapter 4 took a novel mixed-methods approach to assessing paradigm concepts of drought and DRM, in a commentary-style narrative review designed following the identification of conceptual barriers to DRM in Chapter 3 (Objective 3). Using expert interview accounts of management during the Horn of Africa 2021 – 2023 drought and groundwater data collected in Somaliland, it is novel in reviewing whether existing paradigm concepts in the literature reflect the modern operational objectives and practical realities of drought management. The study first found that practical realities do not accord with the literature's paradigm representation that agricultural droughts precede hydrological droughts. For manifold reasons, such as complex hydrogeology and non-linear human abstraction behaviours, negative anomalies in groundwater or fluvial stores can precede those measured in agricultural and soil moisture stores. Therefore, to avert an incorrect inference that agricultural shortages are likely to precede water shortages, the conclusions recommended the omission of drought propagation concepts from drought DRM frameworks.

Next, by comparing interview accounts of drought DRM actions taken in the Horn of Africa with definitions of mitigation, preparedness, response and recovery from the common DRM framework (UNDRR, 2016), the findings demonstrate conceptual issues with applying the preparedness concept to drought. The common perception of the term 'preparedness' as referring to preparation for events occurring in the future creates a conceptual 'grey area' following the physical onset of drought and before the onset of humanitarian emergency response. This 'grey area' fails to attract significant disaster risk financing investments, yet it is an urgent management window of weeks-months where specific and targeted actions can mitigate the translation of physical drought into socio-economic impacts (Coughlan de Perez et al., 2015; Staupe-Delgado and Kruke, 2018). Based on literature and expert applications of the term in the interviews, the study concludes that the 'anticipatory action' conceptual

innovation closely aligns with this window and better describes the unique, evidence-based mitigating actions taken between a drought's first forecast and the onset of humanitarian emergency response (CERF, 2021b; FAO, 2021a; Wilkinson et al., 2020; Guimarães Nobre et al., 2019). In the chapter's conclusions, I recommend the inclusion of anticipatory action in common drought management frameworks together with the concept of 'resilience building', which is conceptually more people-centred and context-specific in its definition and application for pre-disaster activities than the concepts of mitigation and preparedness (Chang and Shinosuka, 2004; Hemond and Robert, 2012; IFRC, 2016). The proposed update of the framework to resilience building – anticipatory action – emergency response – recovery is a pragmatic recommendation based on the updated concepts better reflecting the objectives and operational realities of drought management, as well as the increasing popularity of the resilience building and anticipatory action conceptual innovations in literature and practice relative to traditional DRM concepts (Meadowcroft and Fiorino, 2017; Wilkinson et al., 2020; FAO, 2021a).

8.1.3 Chapter 5 – Localizing Hydrological Drought Early Warning Using In Situ Groundwater Sensors

Chapter 5 addresses the need to assess the practical feasibility of upscaling water monitoring networks in challenging monitoring environments, given their potential humanitarian benefits identified in Chapters 3 and 4 (towards Objective 5). The chapter developed methods of groundwater well simulation that require weeks rather than multiple years of observational data. These findings challenge the multi-year calibration paradigm in groundwater modelling literature, demonstrating that models with short calibrations still improve the data available for drought early warning and humanitarian decision making compared to having no local data inputs at all. The study found that simple lumped groundwater models with short calibrations, trained by just 7-weeks of observations covering both wet and dry season intervals, significantly improve the quantification of local groundwater availabilities when compared to satellite-based indicators frequently used to infer water availability by proxy. The results also presented an appropriate method of groundwater level data analysis and presentation that is tailored to non-expert humanitarian users. Water levels were presented relative to each well's unique critical depth to contextualise water levels in terms of relative water availability, and the model further demonstrated a capability to simulate water levels during historic drought

events for comparison with real-time water levels to support humanitarian decision-making (Objective 4).

8.1.4 Chapter 6 – Unlocking the Benefits of Groundwater Data

Chapter 6 explicitly addressed the practical need for a clearer investment basis for hydrological data (Garrick et al., 2017; Hamel et al., 2020; Pandeya et al., 2016; Stewart, 2015; Sugg, 2021; UN-Water, 2021a), by establishing groundwater monitoring data's potential applications and beneficiaries in the Horn of Africa (Objective 4), as well as the outstanding challenges for sustainable monitoring systems and how they can be resolved (Objective 5). Many benefits were identified for 18 different stakeholder groups in the thematic analysis. For Water Resource Managers (WRMs), the primary users of the data, groundwater information is considered to shift methods of WRM towards more evidence-based, proactive and decentralised approaches. Applications of groundwater data were also identified for emergent stakeholders with no prior experience of working with the data, such as for humanitarian financing and parametric insurance applications, if the data can be analysed and tailored to their information needs. The study found that immature technologies, weak institutional capacities, and difficulties of community access and participation are the principal challenges for upscaling monitoring networks. Its conclusions emphasise the need to address these challenges with concurrent investments in technological innovations, institutional capacity building and improved monitoring practices for monitoring systems to achieve long-term sustainability and fully realise their potential value to stakeholders. Expert recommendations for future implementation practices were summarised in a 5-stage framework, detailing perceived best practices through the different stages of groundwater monitoring system setup from preparation (Stage 1) and piloting (Stage 2) through to expansion (Stage 3), institutionalisation (Stage 4) and a fully operational monitoring system (Stage 5).

8.2 Contribution Towards Resolving Data Scarcity in WRM

Through their respective contributions (discussed in Chapter 7.2), Chapters 3 – 6 all advance the investment basis for water monitoring data by elucidating its potential benefits and applications, and Chapters 5 – 6 further advance the feasibility basis of monitoring by improving the technical and operational methods of monitoring. Collectively, the chapters do not entirely resolve the many outstanding knowledge gaps related to data scarcity in WRM, given this study's principal focus on groundwater data, drought and the Horn of Africa compared to other hydrological variables and situational contexts. Furthermore, wider reductionism or generalisation of the findings should be applied cautiously, due to the limitations of sampling representative experts in this study and the locational nuances of the management of these issues (Chapter 7.3). However, by studying the Horn of Africa, where the nexus of issues in groundwater, drought and WRM are especially acute, the research addresses critical knowledge gaps pertaining to the issue of data scarcity, with many of the findings having a wider relevance to international WRM and drought DRM (Chapter 7.3).

The final research chapter (Chapter 6) most explicitly addresses the issue of resolving data scarcity in WRM. Through its novel assessment of the benefits and recommended practical solutions for monitoring, the chapter most directly advances the investment basis for groundwater monitoring systems. Its methods and findings can support two important streams of further research to continue developing the investment base for hydrological data. First, the findings of the mapping can be used to guide quantitative valuations of groundwater data in the Horn of Africa, ensuring that a more complete range of beneficiaries and applications are accounted for. Second, its qualitative methods can be replicated for other hydrological variables and situational contexts to generate a larger global evidence base of the value and feasibility of hydrological data systems. Establishing more confident value propositions and clearer feasibility bases can increase investment in water monitoring systems if communicated effectively to potential investing stakeholders (Chapter 7.4). Therefore, concluding the research with Chapter 6 and its outlined routes to further develop the findings intends to instigate further research, practical solutions and investment towards resolving data scarcity and associated issues in WRM (Chapter 8.3).

8.3 Research Outlook

In Chapters 3 – 6, many knowledge gaps in need of academic research to build upon the findings were identified and elaborated. Here, they are organised into themes and presented in Table 8.1, with an explanation of their importance to policy and practice. In total, 27 areas in need of academic research are detailed. Each of the topics are constructive towards the objective of resolving data scarcity in WRM by improving the investment basis or the practical feasibility of integrated monitoring systems. The abundance of unresolved knowledge gaps exemplifies the role of research scarcity in the subsequent scarcity of water monitoring solutions, as well as, inversely, the potential for academic research to now affect future decisions regarding water monitoring investments.

Table 8.1. Academic research needs identified during the research study and their importance to policy and practice relevant to resolving data scarcity in Water Resources Management (WRM).

Theme	Academic Research Needs	Importance to Policy and Practice
Financing	Qualitative & subsequent quantitative valuations for all hydrological and water security parameters (general, non-context specific).	Elucidates the value of water monitoring data as a basis for their investment.
	Deductive, quantitative system-level valuations for water monitoring systems in low- and middle-income countries.	Elucidates the value of water monitoring systems as a basis for their large-scale, long-term investment.
	Evaluations of the relationships between water availability, water security and food security in different contexts.	Establishing the link enables the forecasting of water and food security from hydrological data. Attracts investment in WRM from broader development-interested stakeholders.
	Political barriers to disaster risk management (DRM) financing and how to solve those barriers.	Provides a more complete assessment of causes of low investment in DRM for their resolution.
	Potential for indexing agricultural microinsurance and drought parametric insurance by in-situ water monitoring data.	Resolving the monitoring scarcity, basis risk barrier to greater asset insurance can unlock pre-positioned finance for timely, index-based drought and asset financing.
	Detailed study of how to integrate water monitoring data into ex-ante	Creating a clearer feasibility basis and pathway for water monitoring

	humanitarian financing mechanisms, through a deeper interview study of financing stakeholders.	data indexed humanitarian financing can encourage their development.
Users	Communication methods for water monitoring data according to different user needs.	Optimised communications increase value realisation of monitoring data.
	Rebranding of water monitoring to investors and users.	Attracts investment in water monitoring data and its engagement by users.
	Innovative communication of water monitoring analysis to users of low data-literacy.	Formalising methods and best-practices for qualitative discourse and quantitative data communication to low-literacy users is under-researched for water monitoring data. It optimises the data's value realisation.
	Training and capacity-building methods for WRM stakeholders in low- and middle-income countries.	Theory of how to optimise and structure capacity building can increase efficacy and investment.
	Perceptions in other sectors of water security's importance to their practice.	Identifies sectors undervaluing water to appeal to with rebranding and communications. Attracts users and investment.
Implementation	Development of affordable in-situ hydrological sensors with commercial reliability, easy implementation and real-time transmission (e.g., local rainfall, groundwater level, river level, water quality sensors).	Existing sensors are not yet fit for commercial purpose, despite sufficiently advanced technology. Fit-for-purpose sensors can be developed ready for operationalisation.
	More reliable methods of data-transmission in signal-poor areas.	Enables automated monitoring in hard-to-reach areas.
	Technical and institutional structuring of national and district information management centres; potential for integration with existing Early Warning Systems (EWSs).	Lack of framework for their setup prohibits investment and may reduce their efficacy in data management.
	Best practices for operationalisation of densely gauged hydrological monitoring systems in low- and middle-income countries.	Guidance for legal setup, funding mechanisms, staffing, reporting, community engagement, information management, data access rights, and other issues of governance.
	Water prices as a predictor for food insecurity in drought-prone regions.	It is an easy early warning index, and a potential proxy for water security, that can expedite investments in food security anticipatory and humanitarian response actions.
	Integration of water and food household surveys.	Can increase the density of water security data for WRM valuations and as a predictor of food insecurity, migration and other humanitarian needs.

	Negative externalities of dense hydrological data networks in low- and middle-income countries.	The availability of these data creates potential for water corruption, influencing of migration, aquifer over-development and other externalities that need to be assessed and mitigated during operationalisation.
Data Analysis	User-centred design of online platform(s) and mobile applications for water monitoring data communication that is tailored to different user groups.	Optimised communication increases value and accessibility of insights to users.
	Hydrological data insights useful for each user group (e.g. groundwater pumping rates, well efficiency, annual mean decrease).	The variable information needs of specific water monitoring insights have not been established for different user groups, so this can optimise value to users.
	Methods for developing local, in-situ data calibrated hydrological system models in densely gauged catchments with outputs for low- and middle-income context users.	Building on Chapter 5 in this study, calibrated local hydrological models can provide higher-confidence outputs than global, satellite-data inputted models for decision-making.
	Assessments of the degree of confidence required in modelled or forecasted hydrological variables for their actioning by different users.	Establishing sufficient confidence levels ensures models are designed appropriately to local information needs to generate value, whilst avoiding unnecessary complexities or costs.
Actioning Data	Easy-to-use framework for calculating local, context-specific (qualitative and quantitative) valuations of WRM actions using locally collected water and humanitarian monitoring data.	The context-specific nature of WRM requirements means local valuations are needed to justify investments in WRM capacity and actions. A rapid system of local valuation may enable fast, index-based mechanisms for financing actions assessed to have sufficient potential value.
	Inductive assessments of how to resolve the other political, access and physical barriers to resilient WRM.	These less frequently mentioned barriers to WRM (Chapter 3) have not been fully explored in this research and are important in understanding how to resolve low WRM capacities in low- and middle-income countries.
Operationalisation	Pilot projects of dense water monitoring networks, tailored according to user information needs, in different context catchments in low- and middle-income countries.	High-density monitoring at the catchment scale simulates the many of the implementation challenges that monitoring will face at national system-scale, enabling the design of solutions to those challenges before upscaling.
	Long-term, continuous evaluation of monitoring systems once they are operational.	Establishes best practices for other monitoring systems. Enables continuous improvements and

		optimisation of the sustainability and value generated by the monitoring system. Evaluations can be used to justify investment in monitoring systems elsewhere.
Other	Studies of the relationship between water insecurity and conflict at the process-level in Sub-Saharan Africa. Subsequently, also, the relationship between improved water governance and reduced conflict risk.	A demonstrated link between water insecurity and conflict can attract investment from wider political and development sectors to focus on improvements in WRM to reduce risk of conflict and its externalities.

9 Bibliography

Abay, K. A., Abay, M. H., Berhane, G., Chamberlin, J., Croke, K., & Tafere, K. (2022). Access to health services, food, and water during an active conflict: Evidence from Ethiopia. PLOS Global Public Health, 2(11), e0001015. https://doi.org/10.1371/journal.pgph.0001015

Abdulahi, M. O. (2021). GIS Based on Identification of Potential Runoff Sites in Maroodijeeh Catchment, Somaliland. *Delhi Technological University,* TD – 5192. http://dspace.dtu.ac.in:8080/jspui/handle/repository/18423

Action Against Hunger. (2023). *The World's Water Funding Crisis. How donors are missing the mark.* https://www.actionagainsthunger.org.uk/wp-content/uploads/2023/03/2023-WaterFundingGapReport.pdf

Adams, E. A., Sambu, D., & Smiley, S. L. (2019). Urban water supply in Sub-Saharan Africa: Historical and emerging policies and institutional arrangements. *International Journal of Water Resources Development*, *35*(2), 240–263. https://doi.org/10.1080/07900627.2017.1423282

Adams, R. J., Smart, P., & Huff, A. S. (2017). Shades of Grey: Guidelines for Working with the Grey Literature in Systematic Reviews for Management and Organizational Studies. International Journal of Management Reviews, 19(4), 432–454. https://doi.org/10.1111/ijmr.12102

Addor, N., Do, H. X., Alvarez-Garreton, C., Coxon, G., Fowler, K., & Mendoza, P. A. (2020). Large-sample hydrology: Recent progress, guidelines for new datasets and grand challenges. Hydrological Sciences Journal, 65(5), 712–725. https://doi.org/10.1080/02626667.2019.1683182

Adelana, S. (2009). Monitoring and modeling groundwater use in Sub-Saharan Africa: Issues and challenges. *IAHS Publ*, *334*(1).

Adeyeye, K., Gibberd, J., & Chakwizira, J. (2020). Water marginality in rural and peri-urban communities. Journal of Cleaner Production, 273, 122594. https://doi.org/10.1016/j.jclepro.2020.122594

Adloff, M., Singer, M. B., MacLeod, D. A., Michaelides, K., Mehrnegar, N., Hansford, E., Funk, C., & Mitchell, D. (2022). Sustained Water Storage in Horn of Africa Drylands Dominated by Seasonal Rainfall Extremes. Geophysical Research Letters, 49(21), e2022GL099299. https://doi.org/10.1029/2022GL099299

AghaKouchak, A., Mirchi, A., Madani, K., Di Baldassarre, G., Nazemi, A., Alborzi, A., Anjileli, H., Azarderakhsh, M., Chiang, F., Hassanzadeh, E., Huning, L. S., Mallakpour, I., Martinez, A., Mazdiyasni, O., Moftakhari, H., Norouzi, H., Sadegh, M., Sadeqi, D., Van Loon, A. F., & Wanders, N. (2021). Anthropogenic Drought: Definition, Challenges, and

Opportunities. Reviews of Geophysics, 59(2), e2019RG000683. https://doi.org/10.1029/2019RG000683

Ahmed, Z., Ataullahjan, A., Gaffey, M. F., Osman, M., Umutoni, C., Bhutta, Z. A., & Dalmar, A. A. (2020). Understanding the factors affecting the humanitarian health and nutrition response for women and children in Somalia since 2000: A case study. Conflict and Health, 14(1), 35. https://doi.org/10.1186/s13031-019-0241-x

Ajoge, D.O. (2019). Using citizen science in monitoring groundwater levels to improve local groundwater governance, West coast, South Africa. *University of Western Cape Magister Scientiae MSc (Environ & Water Science)*, 27.

Alaerts, G. J. (2019). Financing for Water—Water for Financing: A Global Review of Policy and Practice. Sustainability, 11(3), Article 3. https://doi.org/10.3390/su11030821

Ali, M. Y. (2009) Geology and coal potential of Somaliland. *International Journal of Oil, Gas and Coal Technology*, 2(2), 168-185.

Anderson, W., Taylor, C., McDermid, S., Ilboudo-Nébié, E., Seager, R., Schlenker, W., Cottier, F., de Sherbinin, A., Mendeloff, D., & Markey, K. (2021). Violent conflict exacerbated drought-related food insecurity between 2009 and 2019 in sub-Saharan Africa. Nature Food, 2(8), Article 8. https://doi.org/10.1038/s43016-021-00327-4

Andree, B. P. J., Chamorro, A., Kraay, A., Spencer, P., & Wang, D. (2020). *Predicting Food Crises.* World Bank. https://doi.org/10.1596/1813-9450-9412

Ascott, M. J., Macdonald, D. M. J., Sandwidi, W. J. P., Black, E., Verhoef, A., Zongo, G., Tirogo, J., & Cook, P. (2022). Time of emergence of impacts of climate change on groundwater levels in sub-Saharan Africa. *Journal of Hydrology*, *612*, 128107. https://doi.org/10.1016/j.jhydrol.2022.128107

Ascott, M.J., Macdonald, D.M.J., Black, E., Verhoef, A., Nakohoun, P., Tirogo, J., Sandwidi, W.J.P., Bliefernicht, J., Sorensen, J.P.R. and Bossa, A.Y. (2020). In Situ Observations and Lumped Parameter Model Reconstructions Reveal Intra-Annual to Multidecadal Variability in Groundwater Levels in Sub-Saharan Africa. *Water Resources Research*, 56(12).

Baird, A., O'Keefe, P., Westgate, K.N., & Wisner, B. (1975). *Towards an explanation and reduction of disaster proneness. Occasional paper no.11.* University of Bradford.

Balfour, N. (2023). *Anticipatory action in Somalia's water sector.* https://www.sparc-knowledge.org/news-blog/blog/anticipatory-action-somalias-water-sector

Barter, D. (2019). Poor rains, persisting drought deepens crisis in Somalia and Somaliland. *Oxfam in Horn, East and Central Africa*. https://heca.oxfam.org/latest/press-release/poor-rains-persisting-drought-deepens-crisis-somalia-and-somaliland

Barun, J. (2019). *Public Private Partnership (PPP) in Urban Water Supply System A Review Study of Somalia*. UNICEF.

Basolo, V., Steinberg, L. J., Burby, R. J., Levine, J., Cruz, A., & Huang, C. (2009). The effects of confidence in government and information on perceived and actual preparedness for disasters. *Environment and Behavior.* 41(3), 338-364.

Baumeister, R. F., & Leary, M. R. (1997). Writing Narrative Literature Reviews. Review of General Psychology, 1(3), 311–320. https://doi.org/10.1037/1089-2680.1.3.311

Bedrosian, N., D'Mello Guyett, L., Mitchell, E., & Lantagne, D. (2021). *Review of WASH Severity Classification.* Tufts University.

Beven, K. (1989) Changing ideas in hydrology – The case of physically-based models. *Journal of Hydrology*, 105(1-2), 157-172.

Beven, K. (2001). How far can we go in distributed hydrological modelling? *Hydrology and Earth System Sciences*, 5(1), 1–12.

Bjornlund, V., Bjornlund, H., & van Rooyen, A. F. (2020). Exploring the factors causing the poor performance of most irrigation schemes in post-independence sub-Saharan Africa. International Journal of Water Resources Development, 36(sup1), S54–S101. https://doi.org/10.1080/07900627.2020.1808448

Blauhut, V., Stoelzle, M., Ahopelto, L., Brunner, M. I., Teutschbein, C., Wendt, D. E., Akstinas, V., Bakke, S. J., Barker, L. J., Bartošová, L., Briede, A., Cammalleri, C., Kalin, K. C., De Stefano, L., Fendeková, M., Finger, D. C., Huysmans, M., Ivanov, M., Jaagus, J., Jakubínský, J., Krakovska, S., Laaha, G., Lakatos, M., Manevski, K., Neumann Andersen, M., Nikolova, N., Osuch, M., van Oel, P., Radeva, K., Romanowicz, R. J., Toth, E., Trnka, M., Urošev, M., Urquijo Reguera, J., Sauquet, E., Stevkov, A., Tallaksen, L. M., Trofimova, I., Van Loon, A. F., van Vliet, M. T. H., Vidal, J.-P., Wanders, N., Werner, M., Willems, P., & Živković, N. (2022). Lessons from the 2018–2019 European droughts: a collective need for unifying drought risk management, *Nat. Hazards Earth Syst. Sci*., 22, 2201–2217. https://doi.org/10.5194/nhess-22-2201-2022.

Boluwade, A. (2020). Remote sensed-based rainfall estimations over the East and West Africa regions for disaster risk management. *ISPRS Journal of Photogrammetry and Remote Sensing*, 167, 305–320.

Bosco, F. J. (2006). Actor-Network Theory, Networks, and Relational Approaches in Human Geography. *Approaches to Human Geography*, 136–146. SAGE Publications Ltd. https://doi.org/10.4135/9781446215432

Bosher, L., Chmutina, K., & van Niekerk, D. (2021). Stop going around in circles: towards a reconceptualisation of disaster risk management phases. *Disaster Prevention and Management*. 30 (4/5), 525-537. https://doi.org/10.1108/DPM-03-2021-0071

Bowell, A., Salakpi, E. E., Guigma, K., Muthoka, J. M., Mwangi, J., & Rowhani, P. (2021). Validating commonly used drought indicators in Kenya. Environmental Research Letters, 16(8), 084066. https://doi.org/10.1088/1748-9326/ac16a2

Braune, E., & Xu, Y. (2010). The Role of Ground Water in Sub-Saharan Africa. Groundwater, 48(2), 229–238. https://doi.org/10.1111/j.1745-6584.2009.00557.x

Brinkmann, S., & Kvale, S. (2018). *Doing Interviews. Qualitative Research Kit*. 55 City Road, London: SAGE Publications Ltd.

Brown, C. M., Lund, J. R., Cai, X., Reed, P. M., Zagona, E. A., Ostfeld, A., Hall, J., Characklis, G. W., Yu, W., & Brekke, L. (2015). The future of water resources systems

analysis: Toward a scientific framework for sustainable water management. Water Resources Research, 51(8), 6110–6124. https://doi.org/10.1002/2015WR017114

Brown, R. R., & Farrelly, M. A. (2009). Delivering sustainable urban water management: A review of the hurdles we face. Water Science and Technology, 59(5), 839–846. https://doi.org/10.2166/wst.2009.028

Brown, S. (2014). *Science for Humanitarian Emergencies and Resilience (SHEAR) scoping study: Annex 3—Early warning system and risk assessment case studies.* SHEAR Technical Report.

Bryant, E. (2004). *Natural Hazards. Second Edition.* Cambridge University Press.

Buchanan-Smith, M. & McCelvey, P. (2018). A review of community-centred early warning early action systems. *Concern Worldwide Technical Report.* https://admin.concern.net/sites/default/files/media/migrated/community_centered_early_warning_early_actions.pdf.

Buytaert, W., Dewulf, A., De Bièvre, B., Clark, J. & Hannah, D. M. (2016). Citizen science for water resources management: toward polycentric monitoring and governance? *J Water Resour Plan Manage,* 142:01816002.

Buytaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T. C., Bastiaensen, J., De Bièvre, B., Bhusal, J., Clark, J., Dewulf, A., Foggin, M., Hannah, D. M., Hergarten, C., Isaeva, A., Karpouzoglou, T., Pandeya, B., Paudel, D., Sharma, K., Steenhuis, T., … Zhumanova, M. (2014). Citizen science in hydrology and water resources: Opportunities for knowledge generation, ecosystem service management, and sustainable development. Frontiers in Earth Science, 2. https://www.frontiersin.org/articles/10.3389/feart.2014.00026

Cabot Venton, C. (2018) *The economics of resilience to drought.* USAID. www.usaid.gov/sites/default/files/documents/1867/Kenya_Economics_of_Resilience_Final_Jan_4_2018_-_BRANDED.pdf

Cabot Venton, C., Fitzgibbon, C., Shitarek, T., Coulter, L. & Dooley, O. (2013). *The economics of early response and resilience: lessons from Kenya and Ethiopia.* DFID. www.gov.uk/government/uploads/system/uploads/attachment_data/file/67330/Econ-Ear-Rec-Res-Full-Report_20.pdf

Calderwood, A.J., Pauloo, R.A., Yoder, A.M. & Fogg, G.E. (2020). Low-Cost, Open Source Wireless Sensor Network for Real-Time, Scalable Groundwater Monitoring. *Wate*r, 12(4), 1066.

Calow, R. C., MacDonald, A. M., Nicol, A. L., & Robins, N. S. (2010). Ground Water Security and Drought in Africa: Linking Availability, Access, and Demand. Groundwater, 48(2), 246–256. https://doi.org/10.1111/j.1745-6584.2009.00558.x

Campbell, L. K., Cheng, H., Svendsen, E., Kochnower, D., Bunting-Howarth, K. (2021) Living with Water: Documenting lived experience and social-emotional impacts of chronic flooding for local adaptation planning. *Cities and the Environment*, 14(1) Article 4.

Cantelmi, R., Di Gravio, G., & Patriarca, R. (2021). Reviewing qualitative research approaches in the context of critical infrastructure resilience. Environment Systems and Decisions, 41(3), 341–376. https://doi.org/10.1007/s10669-020-09795-8

Cap-Net. (2023). *International Capacity Development Network for Sustainable Water Management.* https://cap-net.org/

Carter, M. R., Little, P. D., Mogues, T., & Negatu, W. (2007). Poverty Traps and Natural Disasters in Ethiopia and Honduras. World Development, 35(5), 835–856. https://doi.org/10.1016/j.worlddev.2006.09.010

CERF. (2017). CERF Rapid Response. https://cerf.un.org/sites/default/files/resources/cerf_ag_rapid_response_en.pdf

CERF. (2021a). *CERF Anticipatory Action.* https://cerf.un.org/sites/default/files/resources/211117%20CERF%20Anticipatory%20Action.pdf

CERF. (2021b). Ethiopia Anticipatory Action Drought 2021. https://www.unocha.org/sites/unocha/files/20-RR-ETH-46461_Ethiopia_CERF_Report_Final.pdf

CERF. (2022). *CERF Handbook.* https://cerf.un.org/sites/default/files/resources/2209_CERF_Handbook_Sep2022_1_0.pdf

Cha, S., Cho, Y., Kim, S. J., Lee, Y., Choi, S., Asuming, P., Kim, Y., & Jin, Y. (2018). Cost-benefit analysis of water source improvements through borehole drilling or rehabilitation: An empirical study based on a cluster randomized controlled trial in the Volta Region, Ghana. Global Health Action, 11(1), 1523303. https://doi.org/10.1080/16549716.2018.1523303

Chamberlain, K., Cain, T., Sheridan, J., & Dupuis, A. (2011). Pluralisms in Qualitative Research: From Multiple Methods to Integrated Methods. Qualitative Research in Psychology, 8(2), 151–169. https://doi.org/10.1080/14780887.2011.572730

Chan, K., Schillereff, D. N., Baas, A. C. W., Chadwick, M. A., Main, B., Mulligan, M., O'Shead, F. T., Pearce, R., Smith, T. E. L., van Soesbergen, A., Tebbs, E., Thompson, J. (2020). Low-cost electronic sensors for environmental research: Pitfalls and opportunities. *Progress in Physical Geography: Earth and Environment, 45(3).* https://doi.org/10.1177/0309133320956567

Chang, S. E., & Shinozuka, M. (2004). Measuring Improvements in the Disaster Resilience of Communities. Earthquake Spectra, 20(3), 739–755. https://doi.org/10.1193/1.1775796

Chaves-Gonzalez, J., Milano, L., Omtzigt, D.-J., Pfister, D., Poirier, J., Pople, A., Wittig, J., & Zommers, Z. (2022). Anticipatory action: Lessons for the future. Frontiers in Climate, 4. https://www.frontiersin.org/articles/10.3389/fclim.2022.932336

Christian, J. I., Basara, J. B., Otkin, J. A., Hunt, E. D., Wakefield, R. A., Flanagan, P. X., & Xiao, X. (2019). A Methodology for Flash Drought Identification: Application of Flash Drought Frequency across the United States. *Journal of Hydrometeorology*, 20(5), 833–846. https://doi.org/10.1175/JHM-D-18-0198.1

Clarke, D. J., & Dercon, S. (2016). *Dull Disasters? How planning ahead will make a difference.* Oxford University Press.

Clarke, D. J., & Hill, R. V. (2013). *Cost-Benefit Analysis of the African Risk Capacity Facility.* Intl Food Policy Res Inst.

Coetzee, C., & Niekerk, D. van. (2012). Tracking the evolution of the disaster management cycle: A general system theory approach. Jàmbá: Journal of Disaster Risk Studies, 4(1), Article 1. https://doi.org/10.4102/jamba.v4i1.54

Collier, D., & Elman, C. (2008). Qualitative and Multi-Method Research: Organizations, Publication, and Reflections on Integration (SSRN Scholarly Paper 1750525). https://papers.ssrn.com/abstract=1750525

Condon, L. E., Kollet, S., Bierkens, M. F. P., Fogg, G. E., Maxwell, R. M., Hill, M. C., Fransen, H.-J. H., Verhoef, A., Van Loon, A. F., Sulis, M., & Abesser, C. (2021). Global Groundwater Modeling and Monitoring: Opportunities and Challenges. Water Resources Research, 57(12), e2020WR029500. https://doi.org/10.1029/2020WR029500

Contzen, N., Kollmann, J., & Mosler, H.-J. (2023). The importance of user acceptance, support, and behaviour change for the implementation of decentralized water technologies. *Nature Water*, *1*(2), Article 2. https://doi.org/10.1038/s44221-022-00015-y

Cook, C., & Bakker, K. (2012). Water security: Debating an emerging paradigm. Global Environmental Change, 22(1), 94–102. https://doi.org/10.1016/j.gloenvcha.2011.10.011

Corti, T., Muccione, V., Köllner-Heck, P., Bresch, D., & Seneviratne, S.I. (2009) Simulating past droughts and associated building damages in France. *Hydrol Earth Syst Sci*, 13, 1739–1747. doi:10.5194/hess-13-1739-2009.

Cosgrove, W. J., & Loucks, D. P. (2015). Water management: Current and future challenges and research directions. Water Resources Research, 51(6), 4823–4839. https://doi.org/10.1002/2014WR016869

Costella, C., Jaime, C., Arrighi, J., Perez, E. C. de, Suarez, P., & Aalst, M. van. (2017). Scalable and Sustainable: How to Build Anticipatory Capacity into Social Protection Systems. IDS Bulletin, 48(4), Article 4. https://doi.org/10.19088/1968-2017.151

Coughlan de Perez, E., van den Hurk, B., van Aalst, M. K., Jongman, B., Klose, T., & Suarez, P. (2015). Forecast-based financing: An approach for catalyzing humanitarian action based on extreme weather and climate forecasts. Natural Hazards and Earth System Sciences, 15(4), 895–904. https://doi.org/10.5194/nhess-15-895-2015

Crausbay, S. D., Ramirez, A. R., Carter, S. L., Cross, M. S., Hall, K. R., Bathke, D. J., Betancourt, J. L., Colt, S., Cravens, A. E., Dalton, M. S., Dunham, J. B., Hay, L. E., Hayes, M. J., McEvoy, J., McNutt, C. A., Moritz, M. A., Nislow, K. H., Raheem, N., & Sanford, T. (2017). Defining Ecological Drought for the Twenty-First Century. *Bulletin of the American Meteorological Society*, 98(12), 2543–2550. https://doi.org/10.1175/BAMS-D-16-0292.1

Cressman, D. (2009). A Brief Overview of Actor-Network Theory: Punctualization, Heterogeneous Engineering & Translation. Simon Fraser University. https://summit.sfu.ca/item/13593

Creswell, J. (2009). *Research designs: Qualitative, quantitative, and mixed methods approaches*. Sage.

Cuthbert, M. O. (2014). Straight thinking about groundwater recession, *Water Resour. Res*., 50, 2407– 2424, doi:10.1002/2013WR014060.

Dahir, A., Omar, M., & Abukar, Y. (2023). Internet of things based agricultural drought detection system: Case study Southern Somalia. Bulletin of Electrical Engineering and Informatics, 12(1), Article 1. https://doi.org/10.11591/eei.v12i1.4117

Damania, R., Desbureaux, S., Rodella, A.-S., Russ, J., & Zaveri, E. (2019). Quality Unknown: The Invisible Water Crisis. World Bank Publications.

Danert, K., Adekile, D., & Canuto, J. G. (2020). Striving for Borehole Drilling Professionalism in Africa: A Review of a 16-Year Initiative through the Rural Water Supply Network from 2004 to 2020. *Water*, *12*(12), Article 12. https://doi.org/10.3390/w12123305

Daniels, M. C., Anderson, G., & Ali, B. Y. (2018). *Evaluation of the 2017 Somalia Humanitarian Cash-Based Response. https://www.calpnetwork.org/wp-content/uploads/2020/03/1538990263.2018-08-Somalia-CWG-Eval-Rpt-of-2017-CBA-response-Low-Res-for-email-1.pdf*

Dasgupta, P. (2021). *The Economics of Biodiversity: The Dasgupta Review.* HM Treasury. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/962785/The_Economics_of_Biodiversity_The_Dasgupta_Review_Full_Report.pdf

Depoorter, B. (2006). Horizontal political externalities: the supply and demand of disaster management. *Duke Law Journal* 56: 101–125.

Devereux, S., Jere, P. (2008). *"Choice, Dignity and Empowerment?" Cash and Food Transfers in Swaziland. An evaluation of Save the Children"s Emergency Drought Response, 2007/08.* https://www.calpnetwork.org/wp-content/uploads/2020/03/scf-swaziland-ids-08-finalevaluation-1.pdf

Dewey, J. (1925). *Experience and Nature.* Courier Corporation.

Dickert, N., & Sugarman, J. (2005). Ethical goals of community consultation in research. American Journal of Public Health, 95(7), 1123–1127. https://doi.org/10.2105/AJPH.2004.058933

Dinku, T., Funk, C., Peterson, P., Maidment, R., Tadesse, T., Gadain, H. & Ceccato, P. (2018). Validation of the CHIRPS satellite rainfall estimates over eastern Africa. *Quarterly Journal of the Royal Meteorological Society*, 144 (1), 292–312.

Doyle, L., Brady, A.-M., & Byrne, G. (2009). An overview of mixed methods research. Journal of Research in Nursing, 14(2), 175–185. https://doi.org/10.1177/1744987108093962

Dubois, M., Harvey, P., & Taylor, G. (2018). *Rapid Real-Time Review. DFID Somalia Drought Response.*

https://assets.publishing.service.gov.uk/media/5a8566e4e5274a2e87dc3e43/DFID_Somalia_2017_IRF_Real_Time_Review_FINAL.pdf

Durand, A., Hoffmeister, V., Weikmans, R., Gewirtzman, J., Natson, S., Huq, S. & Roberts, J. T. (2016). *Financing Options for Loss and Damage : a Review and Roadmap. Discussion Paper.* German Development Institute. https://www.idos-research.de/uploads/media/DP_21.2016.pdf

Enfors, E. I., & Gordon, L. J. (2008). Dealing with drought: The challenge of using water system technologies to break dryland poverty traps. Global Environmental Change, 18(4), 607–616. https://doi.org/10.1016/j.gloenvcha.2008.07.006

Esfahanian, E., Nejadhashemi, A. P., Abouali, M., Daneshvar, F., Alireza, A. R., Herman, M. R., & Tang, Y. (2016). Defining drought in the context of stream health. *Ecological Engineering*, 94, 668– 681.

FAO SWALIM (2022) *FAO SWALIM: Somalia Water and Land Information Management Combined Drought Index* https://cdi.faoswalim.org/index/cdi

FAO SWALIM. (2021). FAO SWALIM: Somalia Water and Land Information Management Drought Monitoring. *FAO SWALIM: Somalia Water and Land Information Management.* http://www.faoswalim.org/water-resources/drought/drought-monitoring.

FAO SWALIM. (2023). *Dashboard: SWIMS.* https://swims.faoswalim.org/dashboard/view

FAO. (2003). Re-thinking the approach to groundwater and food security. *FAO Water Reports no. 24.* Rome.

FAO. (2014). Community-based Early Warning Systems: Key Practices for DRR Implementers. *A Field Guide for Disaster Risk Reduction in Southern Africa: Key Practices for DRR Implementers.* http://www.fao.org/3/a-i3774e.pdf

FAO. (2018). Horn of Africa – Impact of Early Warning Early Action. Protecting pastoralist livelihoods ahead of drought. *FAO report.* Rome. .

FAO. (2019). Proactive Approaches to Drought Preparedness - Where are we now and where do we go from here? *FAO White Paper*. Rome.

FAO. (2021a). *Anticipatory action. Changing the way we manage disasters.* https://www.fao.org/3/cb7145en/cb7145en.pdf

FAO. (2021b). GIEWS - Global Information and Early Warning System. *Food and Agriculture Organization of the United Nations.*http://www.fao.org/giews/en/

FAO. (2022). *Data collection and analysis tools for food security and nutrition.* https://www.fao.org/3/cc1865en/cc1865en.pdf

Farr, E., Finnegan, L., Grace, J. & Truscott, M. (2022). *Dangerous Delay 2: The Cost of Inaction. https://resourcecentre.savethechildren.net/pdf/Dangerous-Delay-2-the-Cost-of-Inaction_2022.pdf.pdf/*

Fava, F., & Vrieling, A. (2021). Earth observation for drought risk financing in pastoral systems of sub-Saharan Africa. Current Opinion in Environmental Sustainability, 48, 44–52. https://doi.org/10.1016/j.cosust.2020.09.006

FEWS NET. (2020). *Somalia Key Message Update: 3.5 million people are expected to be in Crisis (IPC Phase 3) from June to September 2020, May 2020.* https://reliefweb.int/report/somalia/somalia-key-message-update-35-million-people-are-expected-be-crisis-ipc-phase-3-june

FEWS NET. (2023). *Famine Early Warning Systems Network*. https://fews.net/

Ford, A., Casey, V., Goverde, R., Newton-Lewis, V., McDonald, A., Upton, K., Ritchie, C., & Pole, H. (2022). *Groundwater: The world's neglected defence against climate change*. Water Aid.

Foster, S., Tuinhof, A., & Van, S. F. (2012). Managed groundwater development for water-supply security in Sub-Saharan Africa: Investment priorities. *Water SA*, *38*(3), 359–366. https://doi.org/10.10520/EJC121560

Foster, T., Furey, S., Banks, B., & Willetts, J. (2018). Functionality of handpump water supplies: A review of data from sub-Saharan Africa and the Asia-Pacific region. International Journal of Water Resources Development, 36(5), 855–869. https://doi.org/10.1080/07900627.2018.1543117

Franzke, C. L. E., & Torelló i Sentelles, H. (2020). Risk of extreme high fatalities due to weather and climate hazards and its connection to large-scale climate variability. Climatic Change, 162(2), 507–525. https://doi.org/10.1007/s10584-020-02825-z

Frommen, T., Gröschke, M. & Schneider, M. (2019) Participatory Groundwater Monitoring in India - Insights from a Case-Study in Jaipur. *Geophysical Research Abstracts,* 21, 2019–1543.

FSNAU. (2011). *Food Security and Nutrition Analysis. Post Gu 2011. Technical Series Report VI. 42*. https://fsnau.org/downloads/FSNAU-Post-Gu-2011-Food-Security-Technical-Series-Report.pdf

FSNAU. (2023a). *FSNAU EW-EA Dashboard*. https://dashboard.fsnau.org/

FSNAU. (2023b). *Somalia Early Warning – Early Action (EW-EA) Dashboard Indicators and Thresholds.* https://dashboard.fsnau.org/application/cache/images/EWEA_Dashboard_Indictor_Thresholds.pdf

Funk, C. (2020). Ethiopia, Somalia and Kenya face devastating drought. Nature, 586(7831), 645–645. https://doi.org/10.1038/d41586-020-02698-3

Funk, C., Shukla, S., Thiaw, W. M., Rowland, J., Hoell, A., McNally, A., Husak, G., Novella, N., Budde, M., Peters-Lidard, C., Adoum, A., Galu, G., Korecha, D., Magadzire, T., Rodriguez, M., Robjhon, M., Bekele, E., Arsenault, K., Peterson, P., … Verdin, J. (2019). Recognizing the Famine Early Warning Systems Network: Over 30 Years of Drought Early Warning Science Advances and Partnerships Promoting Global Food Security. Bulletin of the American Meteorological Society, 100(6), 1011–1027. https://doi.org/10.1175/BAMS-D-17-0233.1

Galletta, A. (2013). *Mastering the Semi-Structured Interview and Beyond: From Research Design to Analysis and Publication*. NYU Press.

Garrick, D. E., Hall, J. W., Dobson, A., Damania, R., Grafton, R. Q., Hope, R., Hepburn, C., Bark, R., Boltz, F., De Stefano, L., O'Donnell, E., Matthews, N., & Money, A. (2017). Valuing water for sustainable development. Science, 358(6366), 1003–1005. https://doi.org/10.1126/science.aao4942

Gavin, R., Haji, H., & Porter, P. (2019). The relative contributions of cereal production, imports, and aid to somali food security. African Journal of Food, Agriculture, Nutrition and Development, 19(3), Article 3. https://doi.org/10.18697/ajfand.86.18025

Gaye, C. B., & Tindimugaya, C. (2019). Review: Challenges and opportunities for sustainable groundwater management in Africa. *Hydrogeology Journal*, *27*(3), 1099–1110. https://doi.org/10.1007/s10040-018-1892-1

Gillette, H. P. (1950). A creeping drought under way. *Water and Sewage Works,* 104–105.

Gleick, P. H. (2014). Water, Drought, Climate Change, and Conflict in Syria. Weather, Climate, and Society, 6(3), 331–340. https://doi.org/10.1175/WCAS-D-13-00059.1

Grafton, R., Biswas, A. K., Bosch, H., Fanaian, S., Gupta, J., Revi, A., Sami, N., & Tortajada, C. (2023). Goals, progress and priorities from Mar del Plata in 1977 to New York in 2023. *Nature Water*, *1*(3), Article 3. https://doi.org/10.1038/s44221-023-00041-4

Green, B. N., Johnson, C. D., & Adams, A. (2006). Writing narrative literature reviews for peer-reviewed journals: Secrets of the trade. Journal of Chiropractic Medicine, 5(3), 101–117. https://doi.org/10.1016/S0899-3467(07)60142-6

Guimarães Nobre, G., Davenport, F., Bischiniotis, K., Veldkamp, T., Jongman, B., Funk, C. C., Husak, G., Ward, P. J., & Aerts, J. C. J. H. (2019). Financing agricultural drought risk through ex-ante cash transfers. Science of The Total Environment, 653, 523–535

Guimarães Nobre, G., Pasqui, M., Quaresima, S., Pieretto, S., & Lemos Pereira Bonifácio, R. M. (2023). Forecasting, thresholds, and triggers: Towards developing a Forecast-based Financing system for droughts in Mozambique. *Climate Services*, 30, 100344. https://doi.org/10.1016/j.cliser.2023.100344

Guled, A. (2017). Somalia's new leader declares drought national disaster. *Associate Press.* https://apnews.com/article/97d80c7f1d0b494f9c55578a2134fa88

Gumucio, T., Greatrex, H., & Lentz, E. (2022). Causal Chains Linking Weather Hazards to Disasters in Somalia. *Weather, Climate, and Society*, *14*(3), 849–860. https://doi.org/10.1175/WCAS-D-21-0165.1

Gumucio, T., Greatrex, H., Macfarlane, A., Philp, T., & Scatliffe, S. (2021). *How to use qualitative research to assess triggers of weather-induced disasters & inform weather risk management design*. The Pennsylvania State University. https://github.com/PSU-AXA-Somalia/Documents/blob/main/PSU_AXAXL_QualitativeUserGuide.pdf

Gure, A. (2021). *The Role of Climate information and Early Warning Systems in Supporting Disaster Risk Reduction in Somalia*. Somalia WASH Cluster. https://reliefweb.int/report/somalia/role-climate-information-and-early-warning-systems-supporting-disaster-risk-reduction

Haddaway, N. R., Collins, A. M., Coughlin, D., & Kirk, S. (2015). The Role of Google Scholar in Evidence Reviews and Its Applicability to Grey Literature Searching. PLOS ONE, 10(9), e0138237. https://doi.org/10.1371/journal.pone.0138237

Haile, G. G., Tang, Q., Li, W., Liu, X., & Zhang, X. (2020). Drought: Progress in broadening its understanding. WIREs Water, 7(2), e1407. https://doi.org/10.1002/wat2.1407

Haile, M. (2005). Weather patterns, food security and humanitarian response in sub-Saharan Africa. Philosophical Transactions of the Royal Society B: Biological Sciences, 360(1463), 2169–2182. https://doi.org/10.1098/rstb.2005.1746

Hallegatte, S. (2012). *A cost-effective solution to reduce disaster losses in developing countries and evacuation. World Bank Policy Research Working Paper*. World Bank. https://elibrary.worldbank.org/doi/abs/10.1596/1813-9450-6058

Hamel, P., Bremer, L. L., Ponette-González, A. G., Acosta, E., Fisher, J. R. B., Steele, B., Cavassani, A. T., Klemz, C., Blainski, E., & Brauman, K. A. (2020). The value of hydrologic information for watershed management programs: The case of Camboriú, Brazil. Science of The Total Environment, 705, 135871. https://doi.org/10.1016/j.scitotenv.2019.135871

Hansen, J., List, G., Downs, S., Carr, E. R., Diro, R., Baethgen, W., Kruczkiewicz, A., Braun, M., Furlow, J., Walsh, K., & Magima, N. (2022). Impact pathways from climate services to SDG2 ("zero hunger"): A synthesis of evidence. Climate Risk Management, 35, 100399. https://doi.org/10.1016/j.crm.2022.100399

Hao, Z., AghaKouchak, A., Nakhjiri, N., & Farahmand, A. (2014). Global integrated drought monitoring and prediction system. Scientific Data, 1(1), Article 1. https://doi.org/10.1038/sdata.2014.1

Hartter, J., Ryan, S. J., MacKenzie, C. A., Parker, J. N., & Strasser, C. A. (2013). Spatially explicit data: Stewardship and ethical challenges in science. PLoS Biology, 11(9), e1001634. https://doi.org/10.1371/journal.pbio.1001634

Hashi, F., Johnston, D., & Kemoh, S. (2016). *Public water utility versus private, the case of Burao and Borama, Somaliland: A comparison of PPP and semi-state water utility management models*. https://repository.lboro.ac.uk/articles/conference_contribution/Public_water_utility_versus_private_the_case_of_Burao_and_Borama_Somaliland_a_comparison_of_PPP_and_semi-state_water_utility_management_models/9594389/1

He, C., Liu, Z., Wu, J., Pan, X., Fang, Z., Li, J., & Bryan, B. A. (2021). Future global urban water scarcity and potential solutions. *Nature Communications*, *12*(1), Article 1. https://doi.org/10.1038/s41467-021-25026-3

Headey, D., Taffesse, A. S., You, L. (2012). Enhancing Resilience in the Horn of Africa. *International Food Policy Research Institute.* IFPRI Discussion Paper 01176.

Helveston, M. N. (2015). Consumer protection in the Age of Big Data. *Washington University Law Review*, 93, 859

Hémond, Y., & Robert, B. (2012). Preparedness: The state of the art and future prospects. Disaster Prevention and Management: An International Journal, 21(4), 404–417. https://doi.org/10.1108/09653561211256125

Hillbruner, C., & Moloney, G. (2012). When early warning is not enough—Lessons learned from the 2011 Somalia Famine. Global Food Security, 1(1), 20–28. https://doi.org/10.1016/j.gfs.2012.08.001

Huffman, G. J., Bolvin, D. T., Nelkin, E. J., Wolff, D. B., Adler, R. F., Gu, G., Hong, Y., Bowman, K. P. & Stocker, E.F. (2007). The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-Global, Multiyear, Combined-Sensor Precipitation Estimates at Fine Scales. *Journal of Hydrometeorology*, 8(1), 38–55.

Hughes, D. A. (2019). Facing a future water resources management crisis in sub-Saharan Africa. Journal of Hydrology: Regional Studies, 23, 100600. https://doi.org/10.1016/j.ejrh.2019.100600

Huho, J. M., Ngaira, J. K. W., Ogindo, H. O. (2011). Living with drought: the case of the Maasai pastoralists of northern Kenya. *Educational Research,* 2(1), 779-789.

Hunger, M., & Döll, P. (2008). Value of river discharge data for global-scale hydrological modeling. Hydrology and Earth System Sciences, 12(3), 841–861. https://doi.org/10.5194/hess-12-841-2008

Hussein, M., Law, C., & Fraser, I. (2021). An analysis of food demand in a fragile and insecure country: Somalia as a case study. Food Policy, 101, 102092. https://doi.org/10.1016/j.foodpol.2021.102092

IFRC. (2016). *World Disasters Report 2016 - Resilience: Saving lives today, investing for tomorrow.* https://reliefweb.int/report/world/world-disasters-report-2016-resilience-saving-lives-today-investing-tomorrow-enar

IFRC. (2020). *World Disasters Report 2020. Come Heat or High Water. Tackling the humanitarian impacts of the climate crisis together.* https://oldmedia.ifrc.org/ifrc/wp-content/uploads/2020/11/20201116_WorldDisasters_Full.pdf

IGAD (2023). *Governance. Somalia*. https://land.igad.int/index.php/countries/somalia

IGRAC. (2020). *National Groundwater Monitoring Programmes. A global overview of quantitative groundwater monitoring networks.* https://www.un-igrac.org/resource/national-groundwater-monitoring-programmes-global-overview-quantitative-groundwater

Ikeda, J. (2021). *Guidance note on Drought Finance. Innovative Financial Instruments for Drought Mitigation, Preparedness, Response and Recovery.* https://www.unccd.int/sites/default/files/2022-09/IWG%20task%20group%20report%203%20Drought%20finance%20.pdf

IMF. (2011). *International Monetary Fund, Market-Based Instruments for International Aviation and Shipping of Climate Finance.* https://www.imf.org/external/np/g20/pdf/110411a.pdf.

IMPACT. (2022). *WASH Severity Classification (WSC): Overview - WSC Light Northeast Nigeria, February 2022*. https://reliefweb.int/report/nigeria/wash-severity-classification-wsc-overview-wsc-light-northeast-nigeria-february-2022

Ingram, W., & Memon, F. A. (2019). Internet of Things innovation in rural water supply in sub-Saharan Africa: A critical assessment of emerging ICT. Waterlines, (2), 71–93. https://doi.org/10.3362/1756-3488.18-00028

IPC. (2022). *Somalia: Acute Food Insecurity Situation May 2022 and Projection June to September 2022.* https://www.ipcinfo.org/ipc-country-analysis/details-map/en/c/1155662/?iso3=SOM

IPCC. (2022). *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press. doi:10.1017/9781009325844.

Jackson, C.R., Wang, L., Pachocka, M., Mackay, J.D. & Bloomfield, J.P. (2016). Reconstruction of multi-decadal groundwater level time-series using a lumped conceptual model. *Hydrological Processes*, 30(18), 3107–3125.

Janzen, S. A., & Carter, M. R. (2019). After the Drought: The Impact of Microinsurance on Consumption Smoothing and Asset Protection. American Journal of Agricultural Economics, 101(3), 651–671. https://doi.org/10.1093/ajae/aay061

Jepson, W. E., Wutich, A., Collins, S. M., Boateng, G. O., & Young, S. L. (2017). Progress in household water insecurity metrics: A cross-disciplinary approach. WIREs Water, 4(3), e1214. https://doi.org/10.1002/wat2.1214

Jones, A. D., Ngure, F. M., Pelto, G., & Young, S. L. (2013). What are we assessing when we measure food security? A compendium and review of current metrics. Advances in Nutrition (Bethesda, Md.), 4(5), 481–505. https://doi.org/10.3945/an.113.004119

Karnieli, A., Agam, N., Pinker, R.T., Anderson, M., Imhoff, M.L., Gutman, G.G., Panov, N. & Goldberg, A. (2010). Use of NDVI and Land Surface Temperature for Drought Assessment: Merits and Limitations. *Journal of Climate.* 23(3), 618–633.

Kchouk, S., Melsen, L. A., Walker, D. W., van Oel, P. R. (2021). A geography of drought indices: mismatch between indicators of drought and its impacts on water and food securities. *Nat. Hazards Earth Syst. Sci.,* 22, 323-344.

Kebede, S., MacDonald, A. M., Bonsor, H. C., Dessie, N., Yehualaeshet, T., Wolde, G., Wilson, P., Whaley, L. & Lark, R. M. (2017). *UPGro Hidden Crisis Research Consortium, Survey 1 Country Report – Ethiopia. British Geological Survey (BGS) Open Report, OR/17/024. https://nora.nerc.ac.uk/id/eprint/516998/*

Kellett, J., & Caravani, A. (2013). *Financing Disaster Risk Reduction. A 20 year story of international aid.* http://cdn-odi-production.s3-website-eu-west-1.amazonaws.com/media/documents/8574.pdf

King-Okumu, C., Orindi, V. A., & Lekalkuli, L. (2019). Chapter 19 - Drought management in the drylands of Kenya: What have we learned? Current Directions in Water Scarcity Research, 2, 277–294. https://doi.org/10.1016/B978-0-12-814820-4.00019-5

Klassert, C., Yoon, J., Sigel, K., Klauer, B., Talozi, S., Lachaut, T., Selby, P., Knox, S., Avisse, N., Tilmant, A., Harou, J. J., Mustafa, D., Medellín-Azuara, J., Bataineh, B., Zhang, H., Gawel, E., & Gorelick, S. M. (2023). Unexpected growth of an illegal water market. Nature Sustainability, 1–12. https://doi.org/10.1038/s41893-023-01177-7

Kombo, O. H., Kumaran, S., & Bovim, A. (2021). Design and Application of a Low-Cost, Low- Power, LoRa-GSM, IoT Enabled System for Monitoring of Groundwater Resources With Energy Harvesting Integration. *IEEE Access*, *9*, 128417–128433. https://doi.org/10.1109/ACCESS.2021.3112519

Konar, M., Garcia, M., Sanderson, M. R., Yu, D. J., & Sivapalan, M. (2019). Expanding the Scope and Foundation of Sociohydrology as the Science of Coupled Human-Water Systems. Water Resources Research, 55(2), 874–887. https://doi.org/10.1029/2018WR024088

Krampe, F., Van de Goor, L., Barnhoorn, A., Smith, E., & Smith, D. (2020). Water Security and Governance in the Horn of Africa. Stockholm International Peace Research Institute. https://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-409025

Kreibich, H., Van Loon, A. F., Schröter, K., Ward, P. J., Mazzoleni, M., Sairam, N., Abeshu, G. W., Agafonova, S., AghaKouchak, A., Aksoy, H., Alvarez-Garreton, C., Aznar, B., Balkhi, L., Barendrecht, M. H., Biancamaria, S., Bos-Burgering, L., Bradley, C., Budiyono, Y., Buytaert, W., … Di Baldassarre, G. (2022). The challenge of unprecedented floods and droughts in risk management. *Nature*, *608*(7921), Article 7921. https://doi.org/10.1038/s41586-022-04917-5

Krige, J. (2001). The 1984 Nobel Physics Prize for Heterogeneous Engineering. Minerva, 39(4), 425–443. https://doi.org/10.1023/A:1012735919366

Krishnamurthy R, P. K., Fisher, J. B., Choularton, R. J., & Kareiva, P. M. (2022). Anticipating drought-related food security changes. Nature Sustainability, 5(11), Article 11. https://doi.org/10.1038/s41893-022-00962-0

Kuhlicke, C., Madruga de Brito, M., Bartkowski, B., Botzen, W., Doğulu, C., Han, S., Hudson, P., Nuray Karanci, A., Klassert, C. J., Otto, D., Scolobig, A., Moreno Soares, T., & Rufat, S. (2023). Spinning in circles? A systematic review on the role of theory in social vulnerability, resilience and adaptation research. Global Environmental Change, 80, 102672. https://doi.org/10.1016/j.gloenvcha.2023.102672

Kumar, P., Verma, M., Wood, M., & Negandhi, D. (2010). *Guidance Manual For the Valuation of Regulating Services*. UNEP. https://www.iwlearn.net/resolveuid/d171a5fb-59da-4b33-8ec6-826f0238541b

Larsson, S. (2009). A pluralist view of generalization in qualitative research. International Journal of Research & Method in Education, 32(1), 25–38. https://doi.org/10.1080/17437270902759931

Law, J. (1987). Technology and Heterogeneous Engineering: The Case of Portuguese Expansion. MIT Press.

Law, J. (1992). Notes on the theory of the actor-network: Ordering, strategy, and heterogeneity. Systems Practice, 5(4), 379–393. https://doi.org/10.1007/BF01059830

Lentz, E., Gottlieb, G., Simmons, C., Maxwell, D. (2020). *Hindsight? The Ecosystem of Humanitarian Diagnostics and Its Application to Anticipatory Action*. Tufts University.

Lewis, J. & Liljedahl, B. (2010). Groundwater surveys in Developing Regions. *Air, Soil and Water Research*, 3.

Lewis, J. (2013). Some realities of resilience: a case-study of Wittenberge. *Disaster Prevention and Management,* 22(1), 48-62.

Liang, X., Lettenmaier, D. P., Wood, E. F., & Burges, S. J. (1994). A simple hydrologically based model of land surface water and energy fluxes for general circulation models, *J. Geophys. Res.*, 99(D7), 14415–14428

Liebmann, B., Hoerling, M. P., Funk, C., Bladé, I., Dole, R. M., Allured, D., Quan, X., Pegion, P., & Eischeid, J. K. (2014). Understanding Recent Eastern Horn of Africa Rainfall Variability and Change. Journal of Climate, 27(23), 8630–8645. https://doi.org/10.1175/JCLI-D-13-00714.1

Lin, J., Qian, T., & Schubert, S. (2022). Droughts and Mega-Droughts. Atmosphere-Ocean, 60(3–4), 245–306. https://doi.org/10.1080/07055900.2022.2086848

Lincoln, Y. S. & Guba, E. (1999). Establishing trustworthiness. *Qualitative research*, 3, 397 – 444.

Lindley, A. (2014). *Questioning 'drought displacement': Environment, politics and migration in Somalia.* https://ora.ox.ac.uk/objects/uuid:1f2e76cc-9e80-44b0-bf02-c4fdd09eeaf5/download_file?file_format=application%2Fpdf&safe_filename=lindley%2B-%2BEnglish.pdf&type_of_work=Journal+article

Little, P. D. (2012). On the Somalia Dilemma: Adding Layers of Complexity to an Already Complex Emergency. African Studies Review, 55(1), 191–195. https://doi.org/10.1353/arw.2012.0018

Little, P. D. (2013). Reflections on the future of pastoralism in the Horn of Africa. *Pastoralism and Development in Africa,* 1, 244 – 249

Lloyd-Hughes, B. (2014). The impracticality of a universal drought definition. Theoretical and Applied Climatology, 117(3), 607–611. https://doi.org/10.1007/s00704-013-1025-7

Loucks, D. P., Stakhiv, E. Z., & Martin, L. R. (2000). Sustainable Water Resources Management. Journal of Water Resources Planning and Management, 126(2), 43–47. https://doi.org/10.1061/(ASCE)0733-9496(2000)126:2(43)

Lovdendal, C. R., & Knowles, M. (2005). *Tomorrow's Hunger: A framework for analysing vulnerability to food insecurity.* https://www.fao.org/3/af140t/af140t.pdf

MacAllister, D. J., MacDonald, A. M., Kebede, S., Godfrey, S., & Calow, R. (2020). Comparative performance of rural water supplies during drought. *Nature Communications*, *11*(1), Article 1. https://doi.org/10.1038/s41467-020-14839-3

MacAllister, D. J., Nedaw, D., Kebede, S., Mkandawire, T., Makuluni, P., Shaba, C., Okullo, J., Owor, M., Carter, R., Chilton, J., Casey, V., Fallas, H., & MacDonald, A. M. (2022).

Contribution of physical factors to handpump borehole functionality in Africa. Science of The Total Environment, 851, 158343. https://doi.org/10.1016/j.scitotenv.2022.158343

MacDonald, A. M., & Calow, R. C. (2009). Developing groundwater for secure rural water supplies in Africa. Desalination, 248(1), 546–556. https://doi.org/10.1016/j.desal.2008.05.100

MacDonald, A. M., Bonsor, H. C., Calow, R. C., Taylor, R. G., Lapworth, D. J., Maurice, L., Tucker, J., & O Dochartaigh, B. E. (2011). *Groundwater resilience to climate change in Africa [Publication - Report]*. British Geological Survey. http://www.bgs.ac.uk/gwresilience

MacDonald, A. M., Bonsor, H. C., Dochartaigh, B. É. Ó., & Taylor, R. G. (2012). Quantitative maps of groundwater resources in Africa. Environmental Research Letters, 7(2), 024009. https://doi.org/10.1088/1748-9326/7/2/024009

Mach, K. J., Kraan, C. M., Adger, W. N., Buhaug, H., Burke, M., Fearon, J. D., Field, C. B., Hendrix, C. S., Maystadt, J.-F., O'Loughlin, J., Roessler, P., Scheffran, J., Schultz, K. A., & von Uexkull, N. (2019). Climate as a risk factor for armed conflict. Nature, 571(7764), Article 7764. https://doi.org/10.1038/s41586-019-1300-6

Machete, I., & Marques, R. (2021). Financing the Water and Sanitation Sectors: A Hybrid Literature Review. Infrastructures, 6(1), Article 1. https://doi.org/10.3390/infrastructures6010009

Mackay, J. D., Jackson, C. R. & Wang, L. (2014). A lumped conceptual model to simulate groundwater level time-series. *Environmental Modelling & Software*, 61, 229.

Maidment, R. I., Grimes, D., Black, E., Tarnavsky, E., Young, M., Greatrex, H., Allan, R. P., Stein, T., Nkonde, E., Senkunda, S. & Alcántara, E. M. U. (2017). A new, long-term daily satellite-based rainfall dataset for operational monitoring in Africa. *Scientific Data*. 4(170063), 170082.

Majid, N., Jelle, M., Adan, G., Daar, A., Abdirahman, K., Hailey, P., Balfour, N., Seal, A., & Maxwell, D. (2022). *Another Humanitarian (and Political) Crisis in Somalia in 2022.* Tufts University.

Mardian, J. (2022). The role of spatial scale in drought monitoring and early warning systems: A review. Environmental Reviews, 30(3), 438–459. https://doi.org/10.1139/er-2021-0102

Margerum, R. D., & Robinson, C. J. (2015). Collaborative partnerships and the challenges for sustainable water management. Current Opinion in Environmental Sustainability, 12, 53–58. https://doi.org/10.1016/j.cosust.2014.09.003

Massey, G. (2019). *Subsistence and Change: Lessons of Agropastoralism in Somalia.* Routledge.

Maxwell, D. G. & Majid, N. (2016). Famine in Somalia: Competing imperatives, collective failures, 2011-12. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780190499389.001.0001

Maxwell, D., & Fitzpatrick, M. (2012). The 2011 Somalia famine: Context, causes, and complications. Global Food Security, 1(1), 5–12. https://doi.org/10.1016/j.gfs.2012.07.002

Maxwell, D., Day, M. & Hailey, P. (2023). *Do Famine Declarations Really Lead to Increased Funding?* Tufts University. https://fic.tufts.edu/publication-item/do-famine-declarations-really-lead-to-increased-funding/

Maxwell, D., Lentz, E., Simmons, C., & Gottlieb, G. (2021). *Early Warning and Early Action for Increased Resilience of Livelihoods in IGAD Region*. Tufts University.

Maystadt, J.-F., & Ecker, O. (2014). Extreme Weather and Civil War: Does Drought Fuel Conflict in Somalia through Livestock Price Shocks? American Journal of Agricultural Economics, 96(4), 1157–1182. https://doi.org/10.1093/ajae/aau010

McKee, T.B., Doesken, N.J. & Kleist, J. (1993). The Relationship of Drought Frequency and Duration to Time Scales. *8th Conference on Applied Climatology, Anaheim, 17-22 January 1993*, 179-184.

McKone, T. E., & Deshpande, A. W. (2005). *Can fuzzy logic bring complex environment problems into focus?* https://pubs.acs.org/doi/pdf/10.1021/es0531632

Meadowcroft, J., & Fiorino, D. J. (2017). *Conceptual Innovation in Environmental Policy*. MIT Press.

Mills, J., Bonner, A., & Francis, K. (2006). The Development of Constructivist Grounded Theory. *International Journal of Qualitative Methods, 5*(1), 25–35. https://doi.org/10.1177/160940690600500103

Mishra, A. K., & Singh, V. P. (2010). A review of drought concepts. *Journal of Hydrology*, 391(12), 202– 216.

Mojtahed, R., Nunes, M. B., Martins, J. T., & Peng, A. (2014). Equipping the Constructivist Researcher: The Combined use of SemiStructured Interviews and Decision Making maps. *Electronic Journal of Business Research Methods*, *12*(2), Article 2.
Mourad, K. A. (2023). Post-conflict development, reviewing the water sector in Somalia. Environment, Development and Sustainability, 25(2), 1326–1350. https://doi.org/10.1007/s10668-021-02096-3

Murray, V., Abrahams, J., Abdallah, C., Ahmed, K., Angeles, L., Benouar, D., Brenes T., Alonso, Chang H., Choe, Cox, S., Douris, J., Fagan, L., Fra Paleo, U., Han, Q., Handmer, J., Hodson, S., Khim, W., Mayner, L., Moody, N., Moraes, L., Osvaldo, Nagy, M., Norris, J., Peduzzi, P., Perwaiz, A., Peters, K., Radisch, J., Reichstein, M., Schneider, J., Smith, A., Souch, C., Stevance A., Triyanti, A., Weir, M., Wright, N. (2021). *Hazard Information Profiles: Supplement to UNDRR-ISC Hazard Definition & Classification Review: Technical Report.* United Nations Office for Disaster Risk Reduction.

Mwadalu, R., & Mwangi, M. (2013). The potential role of sorghum in enhancing food security in semi-arid eastern Kenya: A review. Journal of Applied Biosciences, 71, 5786–5799. https://doi.org/10.4314/jab.v71i1.98826

Naddaf, M. (2023). The world faces a water crisis—4 powerful charts show how. Nature, 615(7954), 774–775. https://doi.org/10.1038/d41586-023-00842-3

Naiga, R., Penker, M., & Hogl, K. (2015). Challenging pathways to safe water access in rural Uganda: From supply to demand-driven water governance. *International Journal of the Commons,* 9(1), Article 1. https://doi.org/10.18352/ijc.480

NASA Worldview. (2022). EOSDIS Worldview. https://worldview.earthdata.nasa.gov/?v=43.64744036723287

Nath, S., & Kirschke, S. (2023). Groundwater Monitoring through Citizen Science: A Review of Project Designs and Results. *Groundwater, 61(4), 481-493*. https://doi.org/10.1111/gwat.13298

Nature Sustainability. (2021). Too much and not enough. *Nat Sustain* 4, 659.

Neal, M. J. (2020). COVID-19 and water resources management: Reframing our priorities as a water sector. Water International, 45(5), 435–440. https://doi.org/10.1080/02508060.2020.1773648

Nelson, E. L., Khan, S. A., Thorve, S., Greenough, P. G. (2020). Modeling pastoralist movement in response to environmental variables and conflict in Somaliland: Combining agent-based modeling and geospatial data. PLoS ONE 15(12): e0244185. https://doi.org/10.1371/journal.pone.0244185

Ngcamu, B. S., & Chari, F. (2020). Drought Influences on Food Insecurity in Africa: A Systematic Literature Review. International Journal of Environmental Research and Public Health, 17(16), Article 16. https://doi.org/10.3390/ijerph17165897

Nicholson, S. E. (2014). A detailed look at the recent drought situation in the Greater Horn of Africa. *Journal of Arid Environments*, 103, 71– 79.

Niemeijer, D., & de Groot, R. S. (2008). Framing environmental indicators: Moving from causal chains to causal networks. Environment, Development and Sustainability, 10(1), 89–106. https://doi.org/10.1007/s10668-006-9040-9

Nijsten, G.-J., Christelis, G., Villholth, K. G., Braune, E., & Gaye, C. B. (2018). Transboundary aquifers of Africa: Review of the current state of knowledge and progress towards sustainable development and management. *Journal of Hydrology: Regional Studies*, *20*, 21–34. https://doi.org/10.1016/j.ejrh.2018.03.004

Noritomo, Y., & Takahashi, K. (2020). Can Insurance Payouts Prevent a Poverty Trap? Evidence from Randomised Experiments in Northern Kenya. The Journal of Development Studies, 56(11), 2079–2096. https://doi.org/10.1080/00220388.2020.1736281

O'Keeffe, J., Buytaert, W., Mijic, A., Brozović, N., & Sinha, R. (2016). The use of semi-structured interviews for the characterisation of farmer irrigation practices. *Hydrology and Earth System Sciences*, *20*(5), 1911–1924. https://doi.org/10.5194/hess-20-1911-2016

OCHA. (2021a). *Somalia: Drought Conditions Situation Update (As of 14 April 2021).* https://reliefweb.int/report/somalia/somalia-drought-conditions-situation-update-14-april-2021

OCHA. (2021b). *High-Level Humanitarian Event on Anticipatory Action: A Commitment to Act before Crises. Co-chairs' statement.* United Nations.

OCHA. (2023a). *Horn of Africa Drought Regional Humanitarian Overview & Call to Action.* *https://reliefweb.int/report/ethiopia/horn-africa-drought-regional-humanitarian-overview-call-action-revised-26-may-2023*

OCHA. (2023b). *Somalia Humanitarian Response Plan.* https://humanitarianaction.info/plan/1133

OCHA. (2023c). *Anticipatory Action Toolkit.* https://anticipatory-action-toolkit.unocha.org/

Ochoa-Tocachi, B. F., Alemie, T. C., Guzman, C. D., Tilahun, S. A., Zimale, F. A., Buytaert, W. & Steenhuis, T. S. (2018). Sensitivity Analysis of the Parameter-Efficient Distributed (PED) Model for Discharge and Sediment Concentration Estimation in Degraded Humid Landscapes. *Land Degradation and Development.* 30(2), 151-165.

Odongo, R. A., De Moel, H., & Van Loon, A. F. (2023). Propagation from meteorological to hydrological drought in the Horn of Africa using both standardized and threshold-based indices. Natural Hazards and Earth System Sciences, 23(6), 2365–2386. https://doi.org/10.5194/nhess-23-2365-2023

Okpara, J. N., Afiesimama, E. A., Anuforom, A. C., Owino, A., & Ogunjobi, K. O. (2017). The applicability of Standardized Precipitation Index: Drought characterization for early warning system and weather index insurance in West Africa. Natural Hazards, 89(2), 555–583. https://doi.org/10.1007/s11069-017-2980-6

Opitz-Stapleton, S., Mayhew, L., Alasia, I. J., Dagane, I. A., Mbeche, I., Sheik, M. A., Nor, S. Y., Harir, A. M., Hassan, A. S. & Egemonye, O. (2022). *Livelihoods, Conflict and Mediation: Somalia.* SPARC.

Osherson, D. N., & Smith, E. E. (1981). On the adequacy of prototype theory as a theory of concepts. *Cognition*, 9(1), 35–58. https://doi.org/10.1016/0010-0277(81)90013-5

Otkin, J. A., Svoboda, M., Hunt, E. D., Ford, T. W., Anderson, M. C., Hain, C., & Basara, J. B. (2018). Flash Droughts: A Review and Assessment of the Challenges Imposed by Rapid-Onset Droughts in the United States. *Bulletin of the American Meteorological Society*, 99(5), 911–919. https://doi.org/10.1175/BAMS-D-17-0149.1

Otkin, J. A., Woloszyn, M., Wang, H., Svoboda, M., Skumanich, M., Pulwarty, R., Lisonbee, J., Hoell, A., Hobbins, M., Haigh, T., & Cravens, A. E. (2022). Getting ahead of Flash Drought: From Early Warning to Early Action. Bulletin of the American Meteorological Society, 103(10), E2188–E2202. https://doi.org/10.1175/BAMS-D-21-0288.1

Ovink, H., Rahimzoda, S., Cullman, J., & Imperiale, A. J. (2023). The UN 2023 Water Conference and pathways towards sustainability transformation for a water-secure world. *Nature Water*, *1*(3), Article 3. https://doi.org/10.1038/s44221-023-00052-1

OED. (2023). *Preparedness.* *https://www.oed.com/dictionary/preparedness_n?tl=true*

Pandeya, B., Buytaert, W., Zulkafli, Z., Karpouzoglou, T., Mao, F., & Hannah, D. M. (2016). A comparative analysis of ecosystem services valuation approaches for application at the local scale and in data scarce regions. *Ecosystem Services*, *22*, 250–259. https://doi.org/10.1016/j.ecoser.2016.10.015

Pape, U. J., & Wollburg, P. R. (2019). Impact of Drought on Poverty in Somalia (SSRN Scholarly Paper No. 3313863). https://papers.ssrn.com/abstract=3313863

Pappenberger, F., Beven, K. J., Hunter, N. M., Bates, P. D., Gouweleeuw, B. T., Thielen, J. & de Roo, A. P. J. (2005) Cascading model uncertainty from medium range weather forecasts (10 days) through a rainfall-runoff model to flood inundation predictions within the European Flood Forecasting System (EFFS). *Hydrol. Earth Syst. Sci.,* 9, 381–393.

Parajka, J., & Blöschl, G. (2008). The value of MODIS snow cover data in validating and calibrating conceptual hydrologic models. Journal of Hydrology, 358(3), 240–258. https://doi.org/10.1016/j.jhydrol.2008.06.006

Patton, M. (2014). *Qualitative Research & Evaluation Methods*. Sage Publications Inc. https://us.sagepub.com/en-us/nam/qualitative-research-evaluation-methods/book232962

Paul, B. K., Groot, J. C., Maass, B. L., Notenbaert, A. M., Herrero, M., & Tittonell, P. A. (2020a). Improved feeding and forages at a crossroads: Farming systems approaches for sustainable livestock development in East Africa. Outlook on Agriculture, 49(1), 13–20. https://doi.org/10.1177/0030727020906170

Paul, J. D. & Buytaert, W. (2018). Citizen Science and Low-Cost Sensors for Integrated Water Resources Management. *Advances in Chemical Pollution, Environmental Management and Protection*, 3, 1-33.

Paul, J. D., Buytaert, W., Allen, S., Ballesteros-Cánovas, J. A., Bhusal, J., Cieslik, K., Clark, J., Dugar, S., Hannah, D. M., Stoffel, M., Dewulf, A., Dhital, M. R., Liu, W., Nayaval, J. L., Neupane, B., Schiller, A., Smith, P. J., & Supper, R. (2018). Citizen science for hydrological risk reduction and resilience building. WIREs Water, 5(1), e1262. https://doi.org/10.1002/wat2.1262

Paul, J. D., Buytaert, W. & Sah, N. (2020b). A Technical Evaluation of Lidar-Based Measurement of River Water Levels. *Water Resources Research*, 56(4).

Pavelic, P., Giordano, M., Keraita, B., Ramesh, V., & Rao, T. (2012). *Groundwater availability and use in Sub-Saharan Africa: A review of 15 countries*. IWMI. https://www.iwmi.cgiar.org/Publications/Books/PDF/groundwater_availability_and_use_in_sub-saharan_africa_a_review_of_15_countries.pdf

Peirce, C. S. (1878). How to make our ideas clear. *Popular Science Monthly,* 12, 286-302.

Perreault, T. (2014). What kind of governance for what kind of equity? Towards a theorization of justice in water governance. Water International, 39(2), 233–245. https://doi.org/10.1080/02508060.2014.886843

Peters, E. (2023). *Propagation of drought through groundwater systems: illustrated in the Pang (UK) and Upper-Guadiana (ES) catchments.* PhD Thesis, Wageningen University.

Peters, L. E. R. (2021). Beyond disaster vulnerabilities: An empirical investigation of the causal pathways linking conflict to disaster risks. *International Journal of Disaster Risk Reduction*, *55*, 102092. https://doi.org/10.1016/j.ijdrr.2021.102092

Pianosi, F., Sarrazin, F. & Wagener, T. (2015). A Matlab toolbox for Global Sensitivity Analysis. *Environmental Modelling & Software*, 70, 80-85.

Pichon, F. (2019) *Anticipatory humanitarian action: what role for the CERF?* https://cerf.un.org/sites/default/files/resources/ODI_Early_Action_Study.pdf

Polit, D. F., & Beck, C. T. (2010). Generalization in quantitative and qualitative research: Myths and strategies. International Journal of Nursing Studies, 47(11), 1451–1458. https://doi.org/10.1016/j.ijnurstu.2010.06.004

Postel, S. (2017). *Replenish: The Virtuous Cycle of Water and Prosperity.* Island Books.

Premand, P., & Stoeffler, Q. (2020). *Do Cash Transfers Foster Resilience? Evidence from Rural Niger. Policy Research Working Paper; No. 9473*. World Bank.

Prince, S.H. (1920). *Catastrophe and social change.* Columbia University.

Rangecroft, S., Rohse, M., Banks, E. W., Day, R., Di Baldassarre, G., Frommen, T., Hayashi, Y., Höllermann, B., Lebek, K., Mondino, E., Rusca, M., Wens, M., & Van Loon, A. F. (2020). Guiding principles for hydrologists conducting interdisciplinary research and fieldwork with participants. Hydrological Sciences Journal, 66(2), 214–225. https://doi.org/10.1080/02626667.2020.1852241

Ranger, N., & Clarke, D. (2018). *Centre for Disaster Protection: What role for disaster risk financing in the UN Central Emergency Response Fund?* https://cerf.un.org/document/centre-disaster-protection-what-role-disaster-risk-financing-un-central-emergency-response

Regasa, D., Godesso, A., & Lietaert, I. (2023). LIVING ON THE MARGINS: The Socio-spatial Representation of Urban Internally Displaced Persons in Ethiopia. International Journal of Urban and Regional Research, 47(3), 369–385. https://doi.org/10.1111/1468-2427.13176

Rinaudo, J.-D. (2002). Corruption and allocation of water: The case of public irrigation in Pakistan. Water Policy, 4(5), 405–422. https://doi.org/10.1016/S1366-7017(02)00037-5

Ringler, C., Choufani, J., Chase, C., McCartney, M., Mateo-Sagasta, J., Mekonnen, D., & Dickens, C. (2018). *Meeting the nutrition and water targets of the Sustainable Development Goals: achieving progress through linked interventions. International Water Management Institute (IWMI). CGIAR Research Program on Water, Land and Ecosystems (WLE).* The World Bank. https://doi.org/10.5337/2018.221

Roberts, J. T., Natson, S., Hoffmeister, V., Durand, A., Weikmans, R., Gewirtzman, J., & Huq, S. (2017). How Will We Pay for Loss and Damage? Ethics, Policy & Environment, 20(2), 208–226. https://doi.org/10.1080/21550085.2017.1342963

Rosch, E. H. (1973). Natural categories. *Cognitive Psychology*. 4(3): 328–350. doi:10.1016/0010-0285(73)90017-0.

Saldana, J. (2021). *The coding manual for qualitative researchers*. https://us.sagepub.com/en-us/nam/the-coding-manual-for-qualitative-researchers/book273583

Samset, K., & Christensen, T. (2017). Ex Ante Project Evaluation and the Complexity of Early Decision-Making. *Public Organization Review*, *17*(1), 1–17. https://doi.org/10.1007/s11115-015-0326-y

Sanchez, R. (2022). *Transboundary aquifers: Challenges and the way forward*. UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000383775

Sarni, W., Stinson, C., Mung, A., Garcia, B., Bryan, S., & Swanborough, J. (2018). *Harnessing the Fourth Industrial Revolution for Water*. World Economic Forum. https://www3.weforum.org/docs/WEF_WR129_Harnessing_4IR_Water_Online.pdf

Saunders, M. N. K., Lewis, P., Thornhill, A., & Bristow, A. (2015). *Understanding research philosophy and approaches to theory development.* Pearson Education.

Saunders, M., Lewis, P., Thornhill, A., & Bristow, A. (2019). *'Research Methods for Business Students' Chapter 4: Understanding research philosophy and approaches to theory development,* 128–171.

Sawalha, I. H. (2020), A contemporary perspective on the disaster management cycle. *Foresight*, 22(4), 469-482. https://doi.org/10.1108/FS-11-2019-0097

Scanlon, B. R., Fakhreddine, S., Rateb, A., de Graaf, I., Famiglietti, J., Gleeson, T., Grafton, R. Q., Jobbagy, E., Kebede, S., Kolusu, S. R., Konikow, L. F., Long, D., Mekonnen, M., Schmied, H. M., Mukherjee, A., MacDonald, A., Reedy, R. C., Shamsudduha, M., Simmons, C. T., … Zheng, C. (2023). Global water resources and the role of groundwater in a resilient water future. *Nature Reviews Earth & Environment*, *4*(2), Article 2. https://doi.org/10.1038/s43017-022-00378-6

Scanlon, B. R., Fakhreddine, S., Rateb, A., de Graaf, I., Famiglietti, J., Gleeson, T., Grafton, R. Q., Jobbagy, E., Kebede, S., Kolusu, S. R., Konikow, L. F., Long, D., Mekonnen, M., Schmied, H. M., Mukherjee, A., MacDonald, A., Reedy, R. C., Shamsudduha, M., Simmons, C. T., … Zheng, C. (2023). Global water resources and the role of groundwater in a resilient water future. *Nature Reviews Earth & Environment*, *4*(2), Article 2. https://doi.org/10.1038/s43017-022-00378-6

Scheihing, K. W., Fraser, C. M., Vargas, C. R., Kukurić, N., & Lictevout, E. (2022). A review of current capacity development practice for fostering groundwater sustainability. *Groundwater for Sustainable Development*, *19*, 100823. https://doi.org/10.1016/j.gsd.2022.100823

Schoeman, J., Allan, C., Finlayson, M. (2016). A new paradigm for water? A comparative review of integrated, adaptive and ecosystem-based water management in the Anthropocene. In: *Revisiting Integrated Water Resources Management.* Routledge.

Schwab, K. (2017). *The Fourth Industrial Revolution*. Crown.

Serele, C. (2019). *Groundwater Early Warning System for the South of Madagascar*. UNICEF. https://www.unicef.org/media/91386/file/Groundwater-Early-Warning-System-for-the-South-of-Madagascar.pdf%20

Sheffield, J., Wood, E. F., Chaney, N., Guan, K., Sadri, S., Yuan, X., Olang, L., Amani, A., Ali, A., Ogallo, L. & Demuth, S. (2014). A drought monitoring and forecasting system for sub-Sahara African water resources and food security. *Bulletin of the American Meteorological Society*, 95(6), 861–882.

Sheffield, J., Wood, E. F., Pan, M., Beck, H., Coccia, G., Serrat-Capdevila, A., & Verbist, K. (2018). Satellite Remote Sensing for Water Resources Management: Potential for Supporting

Sustainable Development in Data-Poor Regions. Water Resources Research, 54(12), 9724–9758. https://doi.org/10.1029/2017WR022437

Sherrod, M. M. (2006). Using Multiple Methods in Qualitative Research Design. *Journal of Theory Construction and Testing,* 10(1), 22-25.

Shi, H., Chen, J., Wang, K., & Niu, J. (2018). A new method and a new index for identifying socioeconomic drought events under climate change: A case study of the East River basin in China. *Science of the Total Environment*, 616, 363– 375.

Simion, M., & Kelp, C. (2020). Conceptual Innovation, Function First. Noûs, 54(4), 985–1002. https://doi.org/10.1111/nous.12302

Simukonda, K., Farmani, R., & Butler, D. (2018). Intermittent water supply systems: Causal factors, problems and solution options. Urban Water Journal, 15(5), 488–500. https://doi.org/10.1080/1573062X.2018.1483522

Sivakumar, M. V. K., Stefanski, R., Bazza, M., Zelaya, S., Wilhite, D., & Magalhaes, A. R. (2014). High Level Meeting on National Drought Policy: Summary and Major Outcomes. Weather and Climate Extremes, 3, 126–132. https://doi.org/10.1016/j.wace.2014.03.007

Slaymaker, T., Johnston, R., Young, S.L., Miller, J. & Staddon, C. (2020). *WASH Policy Research Digest Issue #15: Measuring Water Insecurity (No. #15).* https://waterinstitute.unc.edu/files/2020/07/Issue_15_final.pdf

Smakhtin, V. U., & Schipper, E. L. F. (2008). Droughts: The impact of semantics and perceptions. *Water Policy,* 10(2), 131–143. https://doi.org/10.2166/wp.2008.036

Smith, D. M., Gordon, C., Kittikhoun, A., Molwantwa, J., Pacheco Mollinedo, P., Romdhane, A. B., Shrestha, R., Tindimugaya, C., & McDonnell, R. (2023). Research and innovation missions to transform future water systems. *Nature Water*, *1*(3), Article 3. https://doi.org/10.1038/s44221-023-00049-w

Solomon, N., Birhane, E., Gordon, C., Haile, M., Taheri, F., Azadi, H., & Scheffran, J. (2018). Environmental impacts and causes of conflict in the Horn of Africa: A review. Earth-Science Reviews, 177, 284–290. https://doi.org/10.1016/j.earscirev.2017.11.016

Solinst. (2021). *Sonic water level meter.* *https://www.solinst.com/products/level-measurement-devices/104-sonic-water-level-meter/104.php*

Stahl, K. (2001). *Hydrological drought—a study across Europe.* PhD Thesis, Albert-Ludwigs-Universität.

Staupe-Delgado, R., & Kruke, B. I. (2018). Preparedness: Unpacking and clarifying the concept. Journal of Contingencies and Crisis Management, 26(2), 212–224. https://doi.org/10.1111/1468-5973.12175

Staupe-Delgado, R., & Rubin, O. (2022). Challenges Associated with Creeping Disasters in Disaster Risk Science and Practice: Considering Disaster Onset Dynamics. International Journal of Disaster Risk Science, 13(1), 1–11. https://doi.org/10.1007/s13753-022-00391-9

Stephens, E., Coughlan de Perez, E., Kruczkiewicz, A., Boyd, E. & Suarez, P. (2015). Forecast-based Action. *University of Reading, Reading, UK (2015),* 41.

Stewart, B. (2015). Measuring what we manage – the importance of hydrological data to water resources management. *Hydrological Sciences and Water Security: Past, Present and Future. IAHS Publ.* 366, 80-85.

Sudmeier-Rieux, K. (2014). Resilience – an emerging paradigm of danger or of hope? *Disaster Prevention and Management,* 23(1), 67-80.

Sugg, Z. (2022). Social barriers to open (water) data. WIREs Water, 9(1), e1564. https://doi.org/10.1002/wat2.1564

Sutanto, S.J., van der Weert, M., Wanders, N., Blauhut, V. & Van Lanen, H.A.J. (2019). Moving from drought hazard to impact forecasts. *Nature Communications*, 10(1), 1–7.

SWALIM. (2023). *FAO Somalia Water and Land Information Management.*

Sword-Daniels, V., Eriksen, C., Hudson-Doyle, E. E., Alaniz, R., Adler, C., Schenk, T., Vallance, S. (2016) Embodied uncertainty: living with complexity and natural hazards. *Journal of Risk Research*, 21(3) 290-307.

Swyngedouw, E. (2009). The Political Economy and Political Ecology of the Hydro-Social Cycle. Journal of Contemporary Water Research & Education, 142(1), 56–60. https://doi.org/10.1111/j.1936-704X.2009.00054.x

Tallaksen, L. & Van Lanen, H. (2004). Hydrological drought: processes and estimation methods for streamflow and groundwater. *Developments in Water Science.* (48) 40-50. Amsterdam, the Netherlands: Elsevier Science B.V.

Tantoh, H. B., Simatele, D. M., Ebhuoma, E., Donkor, K., & McKay, T. J. M. (2021). Towards a pro-community-based water resource management system in Northwest Cameroon: Practical evidence and lessons of best practices. GeoJournal, 86(2), 943–961. https://doi.org/10.1007/s10708-019-10085-3

Thomas, D. R. (2016). Feedback from research participants: Are member checks useful in qualitative research? Qualitative Research in Psychology, 14(1), 23–41. https://doi.org/10.1080/14780887.2016.1219435

Thomas, E., Jordan, E., Linden, K., Mogesse, B., Hailu, T., Jirma, H., Thomson, P., Koehler, J., & Collins, G. (2020). Reducing drought emergencies in the Horn of Africa. Science of The Total Environment, 727, 138772. https://doi.org/10.1016/j.scitotenv.2020.138772

Thomas, E., Wilson, D., Kathuni, S., Libey, A., Chintalapati, P., & Coyle, J. (2021). A contribution to drought resilience in East Africa through groundwater pump monitoring informed by in-situ instrumentation, remote sensing and ensemble machine learning. *Science of The Total Environment*, *780*, 146486. https://doi.org/10.1016/j.scitotenv.2021.146486

Tozier de la Poterie, A., Castro, E., Rahaman, H., Heinrich, D., Clatworthy, Y., & Mundorega, L. (2023). Anticipatory action to manage climate risks: Lessons from the Red Cross Red Crescent in Southern Africa, Bangladesh, and beyond. *Climate Risk Management*, 39, 100476. https://doi.org/10.1016/j.crm.2023.100476

Tuckey, M. R., & Brewer, N. (2003). The influence of schemas, stimulus ambiguity, and interview schedule on eyewitness memory over time. *Journal of Experimental Psychology: Applied,* 9, 101–118.

Twomlow, A., Grainger, S., Cieslik, K., Paul, J. D., Buytaert, W. (2022). A user-centred design framework for disaster risk visualisation. *International Journal of Disaster Risk Reduction*. (77) 103067.

UCSB. (2021). CHIRPS-GEFS Climate Hazards Center - UC Santa Barbara. https://chc.ucsb.edu/data/chirps-gefs

UN DESA. (2022). *The Sustainable Development Goals Report 2022*. https://unstats.un.org/sdgs/report/2022/

UN. (2015). *Transforming our world: The 2030 Agenda for Sustainable Development*. https://documents-dds-ny.un.org/doc/UNDOC/GEN/N15/291/89/PDF/N1529189.pdf?OpenElement

UN. (2016). *Too important to fail – addressing the humanitarian financing gap. High-Level Panel on Humanitarian Financing Report to the Secretary General.* World Humanitarian Summit. https://reliefweb.int/report/world/high-level-panel-humanitarian-financing-report-secretary-general-too-important-fail

UN. (2023). *UN / Somalia Humanitarian Response* [Video]. UN Audiovisual Library. https://www.unmultimedia.org/avlibrary/asset/3009/3009586/

UNCCD. (2022). *Drought in Numbers 2022.* https://www.unccd.int/sites/default/files/2022-05/Drought%20in%20Numbers.pdf

UNDRR. (2015). *Sendai Framework for Disaster Risk Reduction 2015-2030.* https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030

UNDRR. (2016). *Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction.* https://www.preventionweb.net/files/50683_oiewgreportenglish.pdf?_gl=1*1194dp2*_ga*ODk3NjAwMTY0LjE2ODkxODUyNDc.*_ga_D8G5WXP6YM*MTY4OTkzNjY3Ni44LjEuMTY4OTkzNjcxMS4wLjAuMA.

UNESCO. (2022). *United Nations World Water Development Report 2022: groundwater: making the invisible visible.* https://www.unesco.org/reports/wwdr/2022/en/download

UNHCR. (2021). *UNHCR Somalia: Operational Update (1-30 September 2021).* https://reliefweb.int/report/somalia/unhcr-somalia-operational-update-1-30-september-2021

UNHCR. (2022, August 11). *One million people displaced by drought in Somalia [Press release].* https://www.unhcr.org/news/news-releases/one-million-people-displaced-drought-somalia

UNICEF. (2015). *UNICEF/WFP Return on Investment for Emergency Preparedness study. Final report.* https://www.unicef.org/reports/unicefwfp-return-investment-emergency-preparedness-study#:~:text=Using%20data%20from%20three%20pilot,efficient%20humanitarian%20response%20to%20emergencies.

UNISDR. (2009). *UNISDR Terminology on Disaster Risk Reduction (2009).* https://www.undp.org/sites/g/files/zskgke326/files/migration/ge/GE_isdr_terminology_2009_eng.pdf.

UN-Water. (2021a). *Valuing Water.* https://www.unesco.org/reports/wwdr/2021/en

UN-Water. (2021b). *Summary Progress Update 2021: SDG 6 – water and sanitation for all.* https://www.unwater.org/sites/default/files/app/uploads/2021/12/SDG-6-Summary-Progress-Update-2021_Version-July-2021a.pdf

UN-Water. (2022). *UN-Water Summit on Groundwater: highlights and call for commitments.* https://unesdoc.unesco.org/ark:/48223/pf0000385296

Upton, K., Healy, A., Allan, S., Bristow, G., Bukar, Y., Capstick, S., Danert, K., Goni, A., MacDonald, M., Tijana, S., Theis, L. & Whitmarsh, L. (2017). *Risks and resilience of private boreholes in Lagos, Nigeria.* *https://nora.nerc.ac.uk/id/eprint/519948/1/RIGSS_InesonLecture_2017.pdf*

USAID. (2022). *U.S. Government Global Water Strategy 2022-2027*. https://www.globalwaters.org/sites/default/files/us_global_water_strategy_2022.pdf

Van der Molen, M. K., Dolman, A. J., Ciais, P., Eglin, T., Gobron, N., Law, B. E., Meir, P., Peters, W., Phillips, O. L., & Reichstein, M. (2011). Drought and ecosystem carbon cycling. *Agric For Meteorol*, 151, 765– 773.

Van Loon, A. F. (2013). *On the propagation of drought. How climate and catchment characteristics influence hydrological drought development and recovery*. PhD Thesis, Wageningen University. http://edepot.wur.nl/249786

Van Loon, A. F. (2015). Hydrological drought explained. WIREs Water, 2(4), 359–392. https://doi.org/10.1002/wat2.1085

Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A. J., Tallaksen, L. M., Uijlenhoet, R., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangecroft, S., Wanders, N., & Van Lanen, H. A. J. (2016). Drought in the Anthropocene. *Nature Geoscience*, 9(2), Article 2. https://doi.org/10.1038/ngeo2646

Veness, W. A., Butler, A. P., Ochoa-Tocachi, B. F., Moulds, S., & Buytaert, W. (2022). Localizing Hydrological Drought Early Warning Using In Situ Groundwater Sensors. Water Resources Research, 58(8), e2022WR032165. https://doi.org/10.1029/2022WR032165

Venton, P., Venton, C. C., Limones, N., Ward, C., Pischke, F., Engle, N., Wijnen, M., & Talbi, A. (2019). Framework for the Assessment of Benefits of Action or Cost of Inaction for Drought Preparedness. https://doi.org/10.1596/32330

Vitolo, C., Elkhatib, Y., Reusser, D., Macleod, C. J. A., & Buytaert, W. (2015). Web technologies for environmental Big Data. Environmental Modelling & Software, 63, 185–198. https://doi.org/10.1016/j.envsoft.2014.10.007

Vogl, A. L., Goldstein, J. H., Daily, G. C., Vira, B., Bremer, L., McDonald, R. I., Shemie, D., Tellman, B., & Cassin, J. (2017). Mainstreaming investments in watershed services to

enhance water security: Barriers and opportunities. Environmental Science & Policy, 75, 19–27. https://doi.org/10.1016/j.envsci.2017.05.007

Walker, D. P., Birch, C. E., Harsham, J. H., Scaife, A. A., Graham, R. J. & Segele, S. T. (2019). Skill of dynamical and GHACOF consensus seasonal forecasts of East African rainfall. *Climate Dynamics*, 53, 4911-4935.

Walker, D. W., Smigaj, M., & Tani, M. (2021). The benefits and negative impacts of citizen science applications to water as experienced by participants and communities. WIREs Water, 8(1), e1488. https://doi.org/10.1002/wat2.1488

Warsame, A. A., Sheik-Ali, I. A., Hassan, A. A., & Sarkodie, S. A. (2022). Extreme climatic effects hamper livestock production in Somalia. Environmental Science and Pollution Research, 29(27), 40755–40767. https://doi.org/10.1007/s11356-021-18114-w

Warsame, A., Frison, S., & Checchi, F. (2023). Drought, armed conflict and population mortality in Somalia, 2014–2018: A statistical analysis. PLOS Global Public Health, 3(4), e0001136. https://doi.org/10.1371/journal.pgph.0001136

WEF. (2018). *Harnessing the Fourth Industrial Revolution for Water.* https://www3.weforum.org/docs/WEF_WR129_Harnessing_4IR_Water_Online.pdf

Weingartner, L. & Wilkinson, E. (2019). *Anticipatory crisis financing and action: concepts, initiatives, and evidence.* https://www.disasterprotection.org/publications-centre/anticipatory-crisis-financing-and-action

Weingartner, L., Humphrey, A., Sheikh, M. A., Levine, S. (2022). *Obstacles to and opportunities for anticipatory action in Somalia.* SPARC.

Weingartner, L., Pforr, T., Wilkinson, E. (2020). *The evidence base on Anticipatory Action.* https://docs.wfp.org/api/documents/WFP-0000110236/download/

Weiskel, P. K., Vogel, R. M., Steeves, P. A., Zarriello, P. J., DeSimone, L. A., & Ries, K. G. (2007). Water use regimes: Characterizing direct human interaction with hydrologic systems, *Water Resour. Res.*, 43, W04402, doi:10.1029/2006WR005062.

Welle, K., Williams, J., & Pearce, J. (2016). ICTs Help Citizens Voice Concerns over Water – Or Do They? *IDS Bulletin*, *47*(1), Article 1. https://doi.org/10.19088/1968-2016.105

Wendt, D. E., Bloomfield, J. P., Van Loon, A. F., Garcia, M., Heudorfer, B., Larsen, J., Hannah, D. M. (2021). Evaluating integrated water management strategies to inform hydrological drought mitigation. *Nat. Hazards Earth Syst. Sci.,* 21, 3113-3139.

WHO. (2023a). *Drought.* https://www.who.int/health-topics/drought#tab=tab_1

WHO. (2023b). *From insight to action: examining mortality in Somalia*. https://www.emro.who.int/images/stories/somalia/documents/From-Insight-to-Action-Somalia-2023.pdf?ua=1

WHO/UNICEF. (2021). *Water supply, sanitation and hygiene monitoring.* https://www.who.int/teams/environment-climate-change-and-health/water-sanitation-and-health/monitoring-and-evidence/wash-monitoring

Wilhite, D. A., & Glantz, Michael H., "Understanding the Drought Phenomenon: The Role of Definitions" (1985). Drought Mitigation Center Faculty Publications. 20. http://digitalcommons.unl.edu/droughtfacpub/20

Wilhite, D. A., Sivakumar, M. V. K. & Wood, D. A. (2000). *Early Warning Systems for Drought Preparedness and Drought Management.* World Meteorological Organization.

Wilhite, D. A., Svoboda, M. D., & Hayes, M. J. (2007). Understanding the complex impacts of drought: A key to enhancing drought mitigation and preparedness. Water Resources Management, 21(5), 763–774. https://doi.org/10.1007/s11269-006-9076-5

Wilhite, D.A. & Pulwarty, R.S. (2017). Drought and Water Crises: Integrating Science, Management, and Policy, Second Edition. CRC Press. https://doi.org/10.1201/b22009

Wilkinson, E. (2012). Transforming disaster risk management: a political economy approach. https://www.preventionweb.net/files/globalplatform/entry_bg_paper~7555.pdf

Wilkinson, E., Pforr, T., & Weingartner, L. (2020). *Integrating 'anticipatory action' in disaster risk management.* https://cdn.odi.org/media/documents/202004_odi_anticipatory_action_bn_revised.pdf

Wilkinson, E., Weingartner, L., Choularton, R., Bailey, M., Todd, M., Kniveton, D., & Cabot Venton, C. (2018). *Forecasting hazards, averting disasters. Implementing forecast-based early action at scale.* https://cdn.odi.org/media/documents/12104.pdf

WMO. (2021). *WMO Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes (1970 – 2019).* WMO. https://reliefweb.int/report/world/atlas-mortality-and-economic-losses-weather-climate-and-water-extremes-1970-2019

WMO. (2022). *WMO Unified Data Policy*. World Meteorological Organization. https://library.wmo.int/doc_num.php?explnum_id=11256

WMO. (2023). *Guidelines on the Definition and Monitoring of Extreme Weather and Climate Events.* World Meteorological Organization (WMO). https://public.wmo.int/en/resources/library/guidelines-definition-and-characterization-of-extreme-weather-and-climate-events

Wood, E. F., Siegfried D., Schubert, A. W., Wood, C. D., Peters-Lidard, K. C. Mo, A., Mariotti, & Pulwarty, R.S. (2015). Prospects for Advancing Drought Understanding, Monitoring, and Prediction. *Journal of Hydrometeorology*, 16(4), 1636-1657.

World Bank. (2018). *Assessment of Groundwater Challenges & Opportunities in Support of Sustainable Development in Sub-Saharan Africa*.

World Bank. (2022a). *Global Water Security & Sanitation Partnership (GWSP)*. World Bank.

World Bank. (2022b). *World Bank Provides $385 Million to Horn of Africa Countries to Tap Groundwater Potential and Boost Climate Resilience*. The World Bank. https://www.worldbank.org/en/news/press-release/2022/06/08/world-bank-provides-385-million-to-horn-of-africa-countries-to-tap-groundwater-potential-and-boost-climate-resilience

Wutich, A., & Brewis, A. (2014). Food, Water, and Scarcity: Toward a Broader Anthropology of Resource Insecurity. Current Anthropology, 55(4), 444–468. https://doi.org/10.1086/677311

Yeboua, K., & Cilliers, J. (2021). Development prospects for the Horn of Africa countries to 2040. ISS East Africa Report, 2021(42), 1–68. https://doi.org/10.10520/ejc-isear-v2021-n42-a1

Young, S. L. (2021). Viewpoint: The measurement of water access and use is key for more effective food and nutrition policy. *Food Policy*, 104, 102138. https://doi.org/10.1016/j.foodpol.2021.102138

Zadeh, L. (1978). Fuzzy sets as a basis for a theory of possibility. *Fuzzy Set. Syst.*, 1, 3–28.

Zaki, R. (2021). *Unifying the global WASH response with an evidence-based approach: The WASH Severity Classification (WSC).* https://policycommons.net/artifacts/1992952/unifying-the-global-wash-response-with-an-evidence-based-approach/2744717/

Zins, C. (2007). Conceptual approaches for defining data, information, and knowledge. Journal of the American Society for Information Science and Technology, 58(4), 479–493. https://doi.org/10.1002/asi.20508

Zipper, S. C., Stack Whitney, K., Deines, J. M., Befus, K. M., Bhatia, U., Albers, S. J., Beecher, J., Brelsford, C., Garcia, M., Gleeson, T., O'Donnell, F., Resnik, D., & Schlager, E. (2019). Balancing Open Science and Data Privacy in the Water Sciences. Water Resources Research, 55(7), 5202–5211. https://doi.org/10.1029/2019WR025080

Zulkafli, Z., Perez, K., Vitolo, C., Buytaert, W., Karpouzoglou, T., Dewulf, A., De Bièvre, B., Clark, J., Hannah, D. M., & Shaheed, S. (2017). User-driven design of decision support systems for polycentric environmental resources management. *Environmental Modelling & Software*, *88*, 58–73. https://doi.org/10.1016/j.envsoft.2016.10.012