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University of Strathclyde Engineering

Transboundary Aquifer Assessments at the National Scale: Towards Achieving Sustainable Development Goal 6.5

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This thesis is submitted in fulfilment of the requirement for the degree of Doctor of Philosophy, March 2021

Declaration

This thesis is the result of the author's original research. It has been created by the author and has not been previously submitted, in part or whole, to any university or institution for any degree, diploma, or other qualification.

Signed: CMF

Date: 27/03/2021

Acknowledgements

This PhD has been the most difficult and yet rewarding 4 years of my life. I have grown both professionally and personally. However, it would never have been possible without an incredible support system.

First, I would like to express my gratitude to Robert Kalin, who first believed in my ability and has spent the last 4 years training and guiding me through the PhD process. Without him, this PhD wouldn't exist. Secondly, I would like to thank my second supervisor, Francesco Sindico, who has always been there to provide guidance and has particularly helped me establish myself within the transboundary aquifer community. I would also like to acknowledge that this PhD was made possible through the generous funding of the Climate Justice Fund: Water Futures programme by the Scottish Government. Additional support for field work was also given by the Jeremy Willson Fund through the Geological Society of London which I am extremely grateful for. My PhD was greatly strengthened by input and collaboration from our project partners in Malawi. Special mention should go to Muthi Nhlema and his team at Baseflow, and Zion Uka, Modesta Kanjaye, MacPherson Nkhata and Limbikani Banda at the Government of Malawi.

I have had the honour of working with many fantastic people during my time at the University of Strathclyde. Lee Chambers, Alex Miller, Nick Mannix, Craig Murray, Chris Gallagher, Donald Robertson, Marc Addison, Holly Small, Michael Rivett, Amando Borge, Finlay Patterson, Mark Wells, Murray Simpson, James Bonner, Jack Brickell, Jackson Kawala, Ibrahim Hassan and Jamiu Aladejana among many others have helped support me and made my PhD enjoyable. I would also like to thank Chris White who brought me back from the brink during my second year 'slump'.

I 100% would have never survived the past 4 years without the incredible friendship of Jonathan Truslove, Laura Kelly, Izabella Otalega, Billy Andrews, Mark Stillings and Lovisa Andersson. Having you all by my side through this process has been so valuable. No one understands what it is truly like to do a PhD unless you have been through it yourself. Having you all to lean on during the tough times and celebrate with in the good times was vital in getting me to this point. We are bonded for life through this experience and I know we will continue to be friends for a very long time to come.

Outside of academic, my friends have always been there to proof-read, listen to me moan and remind me what real life has to offer. To all my adventure buddies, thank you for keeping me sane. To Alison, my best friend and the sister I wish I had, your friendship throughout not only this PhD, but also the last 10 years, has meant the world to me. Thank you for the adventures, travels, coffee dates, phone calls, wild nights and takeaways.

My passion for education and research was sparked from a young age and my parents have been instrumental in encouraging and supporting me (financially and emotionally) through my university years. Mum, Dad, thank you for always having faith in me every time I announced I was doing another degree. I will be done soon, I promise!

Finally, Calum. Your unshakable belief in my ability and unwavering support has got me to this point. Thank you.

Abstract

'Transboundary aquifer' is the term given to a body of groundwater that is stored in a geological formation that cross an international or state border. Transboundary aquifers thus have the potential to transmit significant volumes of groundwater from one country to another. Transboundary water is a valuable natural resource which accounts for up to 40% of available drinking water and is essential in both agriculture and industry. Transboundary aquifers are, however, poorly understood scientifically and are underrepresented in international law and policy. This thesis addresses the need for countries to examine their transboundary aquifers at a national scale and prioritise them for national and local scale sustainable management. The case study of Malawi and its neighbouring countries of Mozambique, Zambia and Tanzania has been employed to do this.

First, the current understanding of transboundary aquifers is examined highlighting the recent drive for transboundary aquifer management that has been growing since 2000. A critical assessment of the current status of the regional approach taken in assessing and identifying transboundary aquifers using a Malawi case study is presented. The popular approach risks only focusing on large, extensive aquifers and missing out smaller, more national and local scale aquifers that may be of importance at a smaller scale. A case is therefore made for systematic transboundary aquifer assessment along its national border length addressing both regional and minor local aquifer systems.

Following on, a national border based assessment of Malawi's transboundary aquifer units is conducted highlighting how best this approach can be done within a developing country context. A methodology for identifying hotspots within transboundary aquifers that may be vulnerable to the groundwater quality and quantity issues is then presented. This method is applied to the Malawi case study allowing for prioritization of transboundary aquifers for directed local level management based on vulnerability hotspot mapping. Finally, isotopic and geochemical techniques are utilised to examine one of these identified hotspots

more closely. A conceptual model of the selected hotspot is developed to understand the transboundary implications of the area in greater detail and assist in local scale transboundary management.

Throughout the thesis, the themes of multi-scale management of transboundary aquifers within a sustainable development context are also discussed. In order to achieve Sustainable Development Goal 6, and in particular, target 6.5.2, transboundary aquifers need to be understood and managed more effectively. National scale transboundary aquifer assessments, resource prioritization and multi-scale management can assist with this challenge.

Preface

The main content of this thesis was developed as a series of papers published in peer-reviewed journals. Each main research chapter consists of its own abstract, introduction, methodology, results, discussions, and conclusions where appropriate. A preface of text is provided at the beginning of each core chapter to highlight the connections between the chapters assist the reader with the overall flow of the thesis. A postface is then provided at the end of each chapter to highlight how the chapter achieved the research and specific objectives and to provide any additional thesis context as required. The text from each paper has been replicated into the thesis chapter format with figure/table numberings and headings changed where thesis consistency was required. The papers are either published or submitted in the following:

Chapter 4

Fraser, C.M., Kalin, R.M., Rivett, M.O., Nkhata, M., Kanjaye, M. 2018. A national approach to systematic transboundary aquifer assessment and conceptualisation at relevant scales: A Malawi case study. Journal of Hydrology: Regional Studies. Special Issue on International Shared Aquifer Resources Assessment and Management. Vol 20. Pages 35-48. https://doi.org/10.1016/j.ejrh.2018.04.001

Author contribution:

Conceptualization (C.M.F, R.M.K), data curation (C.M.F, R.M.K), formal analysis (C.M.F), investigation (C.M.F), methodology (C.M.F., M.O.R), validation (C.M.F., M.N., M.K.), visualization (C.M.F., M.O.R), project administration (R.M.K), supervision (R.M.K), writing original draft (C.M.F), review and editing (C.M.F., R.M.K., M.O.R., M.N., M.K.)

Chapter 5

Fraser, C.M., Kalin, R.M., Kanjaye, M., Uka, Z. 2020. A National Border-Based Assessment of Malawi's Transboundary Aquifer Units: Towards Achieving Sustainable Development Goal 6.5.2. Journal of Hydrology: Regional Studies. Volume 31, October 2020, 100726. DOI: https://doi.org/10.1016/j.ejrh.2020.100726

Author contribution:

Conceptualization (C.M.F, R.M.K), data curation (C.M.F, R.M.K), formal analysis (C.M.F), investigation (C.M.F), methodology (C.M.F.), validation (C.M.F., M.K., Z.U.), visualization (C.M.F.), project administration (R.M.K), supervision (R.M.K), writing original draft (C.M.F), review and editing (C.M.F., R.M.K.., M.K., Z.U.)

Chapter 6

Fraser, C.M., Kalin, R.M., Kanjaye, M., Uka, Z. 2020. A Methodology to Identify Vulnerable Transboundary Aquifer Hotspots for Multi-Scale Groundwater Management. Water International. 45:7-8, 865-883.
DOI: https://doi.org/10.1080/02508060.2020.1832747

Author contribution:

Conceptualization (C.M.F, R.M.K), data curation (C.M.F, R.M.K), formal analysis (C.M.F), investigation (C.M.F), methodology (C.M.F.), validation (C.M.F., M.K., Z.U.), visualization (C.M.F.), project administration (R.M.K), supervision (R.M.K), writing original draft (C.M.F), review and editing (C.M.F., R.M.K.., M.K., Z.U.)

Chapter 7

Fraser, C.M., Banda, L.C.., Kalin, R.M. 2020. An Isotopic and Geochemical Assessment of the Ruo Transboundary Aquifer System, Malawi-Mozambique. Hydrogeology. Submitted.

Author contribution:

Conceptualization (C.M.F, R.M.K), field work (C.M.F., L.C.B), data curation (C.M.F, L.C.B), laboratory analysis (L.C.B), investigation (C.M.F), methodology (C.M.F., L.C.B.), validation (C.M.F., M.K., Z.U.), Interpretation (C.M.F), visualization (C.M.F.), project administration (R.M.K), supervision (R.M.K), writing original draft (C.M.F), review and editing (C.M.F., R.M.K.., L.C.B.)

Additional Publications (not fully included within thesis)

Publication A (sections of which are reproduced in Chapter 2):

Fraser, C.M., Brickell, J., Kalin, R.M. 2020. Post-Brexit implications for transboundary groundwater management along the Northern Ireland and the Republic of Ireland border. Environmental Research Letters. 15, 044022. https://doi.org/10.1088/1748-9326/ab7392

Author contribution:

Conceptualization (C.M.F, J.B., R.M.K), data curation (C.M.F, J.B), formal analysis (C.M.F, J.B), investigation (C.M.F, J.B), methodology (C.M.F), validation (C.M.F.), visualization (C.M.F), project administration (R.M.K), supervision (R.M.K), writing original draft (C.M.F), review and editing (C.M.F., R.M.K., J.B)

Publication B (not included within the thesis):

Banda, L., Rivett, M., Kalin, R.M., Zavison, A.; Phiri, P.; L.; Chavula, G.; Kapachika, C.; Kamtukule, S, Fraser, C.M., Nhlema, M. 2020. Seasonally Variant Stable Isotope Baseline Characterisation of Malawi's Shire River Basin to Support Integrated Water Resources Management. Water, 12, 1410; https://doi.org/10.3390/w12051410

Author contribution:

Methodology (L.C.B., M.O.R., R.M.K., A.S.K.Z., C.M.F.), validation (L.C.B., M.O.R. and R.M.K.), formal analysis (L.C.B and M.O.R.) investigation,(L.C.B. and M.O.R.), resources (L.C.B. and P.P.), data curation (L.C.B., A.S.K.Z.), writing—original draft preparation (L.C.B.), writing—review and editing (M.O.R., L.C.B., R.M.K., C.M.F., G.C., P.P. and M.N.), visualization (L.C.B., C.K., M.O.R. and C.M.F.), supervision (R.M.K. and M.O.R), project administration (R.M.K., S.K., P.P., M.N. and L.C.B.), funding acquisition (R.M.K., L.C.B., S.K. and P.P.)

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List of Abbreviations and Acronyms

ADB	African Development Bank
APHA	American Public Health Association
BGS	British Geological Survey
CARE	Catchment Actions for Resilient Eco-systems
CJF	Climate Justice Fund: Water Futures Programme
DENSEA	Danish International Development Agency
DISA	Defence Information Systems Agency
EARS	East African rift system
EU	European Union
GEF-TWAP	Global Environment Facility Transboundary Waters Assessment Program
GIS	geographic information system
IAEA	International Atomic Energy Agency
IAH	International association of hydrogeologists
IGRAC	International Groundwater Resources Assessment Centre
ISARM	Internationally Shared Aquifer Resources Management
ILEC	International Lake Environment Committee Foundation
ILC	International Law Commission
IWMI	International Water Management Institute
IWRM	Integrated water resource management
MASDAP	Malawi Spatial Data Platform
MoAIWD	Republic of Malawi Ministry of Agriculture, Irrigation and Water Development
NBI	Nile Basin Initiative
NSAS	Nubian Sandstone Aquifer System
OAU	Organization of African Unity
ORASECOM	Orange-Senqu River Commission
RBO	River Basin Organization
RQ	Research question
SADC	Southern African Development Community
SADC-DW	Southern African Development Community Department of Water

SADC-GMI	Southern African Development Community – Groundwater Management Institute
SASS	Northwestern Sahara Aquifer System
SDG	Sustainable Development Goals
SO	Specific objective
TBA	Transboundary aquifer
UN	United Nations
UNCDP	United Nations Capital Development Fund
UNDESA	United Nations Department of Economic and Social Affairs
UNECA	United Nations Economic Commission for Africa
UNECE	United Nations Economic Commission for Europe
UNEP	United Nations Environmental Programme
UNILC	United Nations International Law Commission
UNEP-DHI	UNEP-DHI Partnership – Centre on Water and Environment
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNESCO-IHP	United Nations Educational, Scientific and Cultural Organization - International Hydrological Programme
UNESCO-IOC	Intergovernmental Oceanographic Commission
UCLG	United Cities and Local Governments
UNWC	United Nations Watercourses Commission
WASH	Water access, sanitation and hygiene
WFD	Water Framework Directive (2000)
WRU	Water resource unit
ZAMCOM	Zambezi Watercourse Commission
WHO	World Health Organization
WMO	World Meteorological Organization

1 Introduction

1.1 Overview

Groundwater is one of the most important natural resources on Earth. Stored in porous rocks and cracks underground called aquifers, groundwater accounts for 98% of the total water resources available to us. When an aquifer crosses an international or political border, it is deemed to be 'transboundary' (UN Water, 2014). These transboundary aquifers thus have the potential for groundwater exchange between neighbouring countries (Wada and Heinrich, 2013). The importance of transboundary water resources has been understood since the 1970's (UN, 1978 in Wolf et al., 1999) and recently has been brought to the international agenda due to its inclusion within the United Nations (UN) Sustainable Development Goals (SDGs) (UN, 2017). Goal 6 of the SDGs calls for water and sanitation for all, and, target 6.5 in particular, requires full integrated water resource management (IWRM) of surface and groundwater at all levels, including through transboundary cooperation where appropriate.

In 2011 the Scottish Government awarded a significant research grant to the University of Strathclyde through the Climate Justice Fund. The project, titled "Climate Justice Fund: Water Futures Programme", was aimed at working with the Government of Malawi to assist the country in achieving Sustainable Development Goal 6. The project had 4 work streams; asset management, policy exchange and support, capacity building, and research and knowledge exchange. As part of the research and knowledge stream, transboundary groundwater resource management was selected as a key focus with the objective of understanding and managing the countries transboundary aquifers better. Subsequently, this PhD, titled "*Transboundary Aquifer Assessments at the National Scale: Towards Achieving Sustainable Development Goal 6.5*" was developed in consultation and cooperation with representatives from the Ministry of Agriculture, Irrigation and Water Development (MoAIWD) in the Government of Malawi to fulfil the aforementioned work stream objective.

This research is focused on the identification and subsequent management of these transboundary aquifers. There is a severe lack of transboundary aquifer identification and assessments at the national and local level due to transboundary aquifer assessments having almost exclusively focused on the regional level over the last decade (European Commission, 2015; Puri & Aureli, 2005; Zektser, 2010). As a consequence, the detail required to understand and manage these transboundary aquifers at a more national and local scale is lacking. The importance of more local and binational transboundary assessments and management has been highlighted in the research of Eckstein (2011) and Eckstein (2012). Research over the past decade has started to move towards increasing assessment and understanding of TBAs in more detail at the national scale, with key examples from Sanchez et al, 2016; Rivea, 2015; Petre et al., 2016 and Petre et al., 2015. However, to date, no studies have looked to understand the transboundary aquifers at a national scale in Africa, where progress is hampered by limited data, weak national water policy, a drive towards river basin focused management and where capacity is often lacking (Smith-Carrington and Chilton 1983; Kalin et al., 2019). Identifying and describing all transboundary aquifers that cross the international border of a single country can allow for prioritized data collection and directed cooperative management, assisting in the achievement of SDG 6.5.2.

Within this thesis, the 'national' scale focuses on Malawi and its direct bordering neighbours. The 'local' scale refers to smaller sub-areas within Malawi. A 'national' scale assessment of a 'transboundary' aquifer is therefore defined as an assessment of a single country's entire transboundary aquifer circumstances Including all transboundary aquifers with all bordering countries in the case of multiple neighbours.

This thesis was developed in response to the need for better science to support transboundary aquifer management at the national and local scale. In order to have good transboundary management and cooperation, you first need a solid and sound understanding of said transboundary aquifer within a country to base it on; You can't manage what you don't measure.

1.2 Research Aims and Objectives

1.2.1 Research Aim

The aim of this research is to: investigate the role that national scale transboundary aquifer assessments can play in sustainable water resources management and establish ways in which national scale transboundary aquifer assessments can be conducted, advocating for multi-scale transboundary aquifer management. To address this research aim, 4 individual research questions were developed each with multiple specific objectives attributed to them.

Malawi was selected as a case study to address the overall research aim as part of the conditions of the scholarship funding from the Scottish Government Water Futures Programme for this PhD. Further interest in Malawi as a research area was twofold. First, the country is known to have issues with water availability and, second, Malawi's geographical position as a landlocked country means that the country has many transboundary neighbours.

1.2.2 Research Questions (RQ) and Specific Objectives (SO)

4 Research Questions and 11 related Specific Objectives were developed to address the research aim and to fill identified knowledge gaps.

RQ1. How have transboundary aquifer assessments up until now allowed for transboundary aquifer management at the national scale?

> *SO1*. With the aid of a case study, critically review assessments that focus on more obvious major aquifer systems. By doing so, identify gaps in current transboundary aquifer knowledge required for a national management strategy.

SO2. Make a case for systematic transboundary aquifer assessment along its national border length addressing minor, local aquifer systems and groundwater/surface water interactions.

SO3. With the aid of a case study, discuss importance and challenges of IWRM in TBA management and assessments

RQ2. Are there more transboundary aquifers than previously thought in Malawi?

SO4. Conduct a national border based assessment of Malawi's transboundary aquifer units.

SO5. Describe the identified transboundary aquifer units shared between Malawi and its neighbours alongside data gaps that will require addressing to move forward.

SO6. Highlight current limitations in transboundary aquifer assessment and management that may need to be addressed in order to achieve the Sustainable Development Goal agenda, specifically target 6.5.

RQ3. Do all transboundary aquifers require detailed assessments, management and agreements governing them?

SO7. Present a methodology for identifying hotspots within transboundary aquifers that may be vulnerable to groundwater quality and quantity issues.

SO8. Prioritise Malawi's transboundary aquifers for directed national and local level management based on vulnerability hotspot mapping

SO9. Discuss the importance of multi-scale management approaches to transboundary aquifers highlighting ways in which institutional organizations and transboundary agreements and arrangements can assist in its implementation

RQ4. What role can geochemical and isotopic analysis play in assessing the transboundary nature of an aquifer?

SO10. Conduct an isotopic and geochemical assessment on a selected hotspot

SO11. Develop a conceptual model of the selected hotspot to understand the transboundary implications of the area in greater detail

1.3 Thesis Structure

The thesis is composed of 8 chapters; an introduction, a short literature review, a methodology, 4 main research components and a conclusions and recommendations chapter. The 4 main research chapters are each represented by an individual peer reviewed paper publication (chapters 4-7). These papers are cumulative and sequential, but, they are also stand-alone publications. 3 of the papers have been published in international peer-reviewed journals and 1 other is submitted and under review. Sections from an additional published paper are included in chapters 2 and 8. Figure 1.1 outlines the structure of the thesis, highlighting the research questions and specific objectives addressed in each chapter.

- An introduction chapter (chapter 1) is given and the beginning of the thesis providing a general introduction to the topic, the main research aim, 4 research questions and 11 specific research objectives that will be answered throughout the thesis. The novelty of the thesis is also presented.

- A short literature review (chapter 2) is presented to set the scene of the thesis, reviewing the current standards and practices within transboundary aquifer assessments and management and indicating key knowledge gaps that will be addressed throughout the thesis. Additional literature is also reviewed within each main chapter (chapter 4-7).

- A methodology chapter (chapter 3) then provides detail on the research philosophy adopted, research materials and the methods used.

- Chapter 4 of the thesis is the first main research chapter and aims to address RQ1 through SO1, SO2 and SO3. Available data and literature was gathered and critically assessed using an integrative approach to identify current gaps in transboundary aquifer assessments within Malawi and the wider Southern African Development Community (SADC) (Synder, 2019). This chapter makes a case for national border based transboundary aquifer assessments. It also presents a series of conceptual models of TBA interactions relevant to the Malawi case study. A discussion then considers how TBA assessments might be integrated to national implementation, strategic policy development and agreements with neighbouring countries. Key research gaps are offered and justification for further research that this thesis addresses is presented.

- Chapter 5 presents a methodology for conducting a national border-based transboundary aquifer assessment and applies the method to the Malawi case study. In doing so, it answers RQ2 through SO64, SO5 and SO6. The common hydrogeological principle that aquifers are defined by lithology changes was adopted to interpret which aquifer units within Malawi crossed its international borders. Transboundary aquifers were then delineated using known hydrogeological water baring units as a basis. Available literature and data was then gathered on hydrogeological characteristics of each transboundary aquifer type and presented in a discussion format. Finally, the chapter highlights current limitations in transboundary aquifer assessment and management that may need to be addressed in order to achieve the Sustainable Development Goal agenda, specifically targeting 6.5.

- Chapter 6 utilises the concept of fuzzy logic to develop a site selection method in order to identify transboundary aquifer hotspots in Malawi. Data from two open source shapefiles (Persits, 2002; Upton et al., 2018; MASDAP, 2019) were used in conjunction with water point survey data from the free data management and visualisation tool ‘mWater’ database (www.mwater.co). Microsoft Excel was used to clean the data and QGIS (version 3.4) was used to spatially present results. Results were then interpreted to provide an indication of which hotspots may need more attention and assessments undertaken over them alongside a discussion of what scale of management may be appropriate for each case. This chapter answers RQ3 through SO7, SO8 and SO9.

- Chapter 7 answers RQ4 through SO10 and SO11. This chapter presents the results of a fieldwork campaign in Malawi and Mozambique on a hotspot identified in chapter 6. Isotope and geochemical analysis was undertaken on 36 groundwater and surface water samples using Excel, Geochemist Workbench Student Edition 14.0, SPSS and QGIS (version 3.4). Results included piper diagrams, scatter diagrams and spatial maps. A conceptual model of the field area was created to aid interpretation of how the transboundary system in the area works. Recommendations for future studies and management are also given highlighting potential transboundary risks to the system.

- Chapter 8 closes the thesis by providing a summary of key findings, an integrated discussion of key themes, recommendations for future practice and recommendations for further research.

- References and appendices are provided at the end of the thesis.

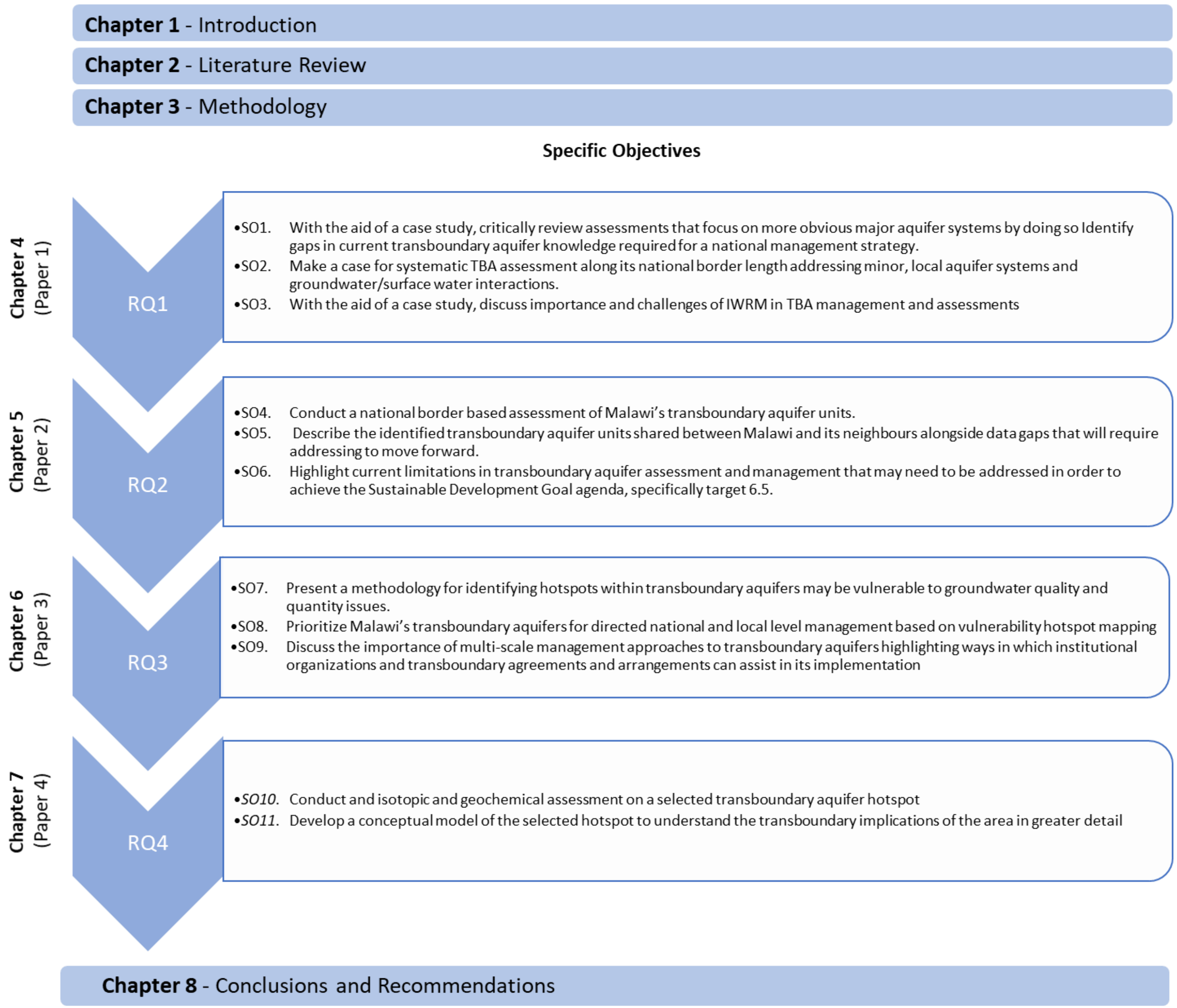


Figure 1.1- Thesis roadmap, highlighting the research questions and specific objectives addressed in each thesis chapter

2 Literature Review

This literature review reviews the current standards and practices within transboundary aquifer assessments and management, and indicates key knowledge gaps addressed throughout the thesis.

2.1 The Importance of Groundwater

Water is the most important natural resource on Earth. Water security drives economic development, health, and welfare (Grey and Sadoff 2007; Hunter et al., 2010). Worldwide, water use is also increasing due to growing water, sanitation and hygiene (WASH) demands. However, over 783 million people across the globe still do not have access to an improved source of drinking water, 40% of which live in Sub-Saharan Africa (UNDESA, 2016). Stored in porous rocks and cracks underground called aquifers, groundwater accounts for around 97% of the total water resources available (i.e. non-frozen) across the globe (IGRAC and UNESCO, 2015a). Groundwater provides almost half of the drinking water worldwide alongside 40% of the water used for irrigated agriculture and 33% for industry (Smith et al., 2016; UN Water, 2018). It is essential for sustaining ecosystems and providing baseflow to rivers (Kelly et al., 2019a). In many countries, groundwater is the only reliable resource for safe water supplies and food security (MacDonald and Calow 2009). Groundwater is often a favourable water source as these systems respond more slowly to meteorological conditions than surface water, and as such provide a natural buffer against climate variability including drought (Calow et al. 1997, 2010). Groundwater also generally doesn't require treatment as it is naturally high quality (MacDonald et al., 2012).

The continent of Africa is heavily reliant upon groundwater, with an estimated 75% of its population dependent on this resource for basic water supplies (Altchenko and Villholth, 2013). It is also essential for rural livelihoods such as livestock rearing and agricultural crop cultivation in many African countries (Villholth, 2013 and Foster et al., 2008 in Nisanje et al., 2018). The population in sub-Saharan Africa is projected to double by 2050 (UN, 2019). Climate change and increasing human impacts on the environment are putting pressure on groundwater resources, causing quality and quantity issues (UN Water, 2018). Over the last decade, groundwater abstraction has tripled and continues to increase at around 2%/year (Van der Gun, 2012).

2.2 Transboundary Aquifers

Water is not bound by political boundaries and can therefore cross country and political borders traveling from one sovereign country or state into another (Wada and Heinrich, 2013). This is termed 'transboundary' water movement. Rivers, lakes and groundwater often are transboundary. In fact, 40% of the water worldwide that we depend upon is estimated to be transboundary (Eckstein, 2017). Transboundary groundwater is stored and transmitted through aquifers which are permeable water-bearing geological units. These are termed 'transboundary aquifers'. Some of these shared aquifers alone have enough water stored in them to provide the drinking water needs of the planet for 200 years (Puri and Naser, 2003). No two aquifers are the same, and this assertion is the same for transboundary aquifers (Eckstein, 2012). Lithology, transmissivity, storage capabilities, abstraction rates, populations dependency, seasonal fluctuations are just some factors that may affect how a (transboundary) aquifer is used (Hiscock and Bense, 2005).

A theoretical conceptual representation of a transboundary aquifer is provided in figure 2.1. The key feature of this figure is that groundwater can be seen to cross an international boundary thus transferring water from one side of the border to the other. The country or state that the groundwater flows from is generally termed the 'upstream' state. The country or state that the groundwater flows in to is termed the 'downstream' state. The delineation of upstream and downstream states (i.e. groundwater flow direction) is essential in transboundary aquifer management as pollution or over-abstraction within the upstream state can have direct implications for those downstream. There are however other variables that can complicate this idealised version of a transboundary aquifer which must be considered in terms of management (Eckstein and Eckstein, 2005).

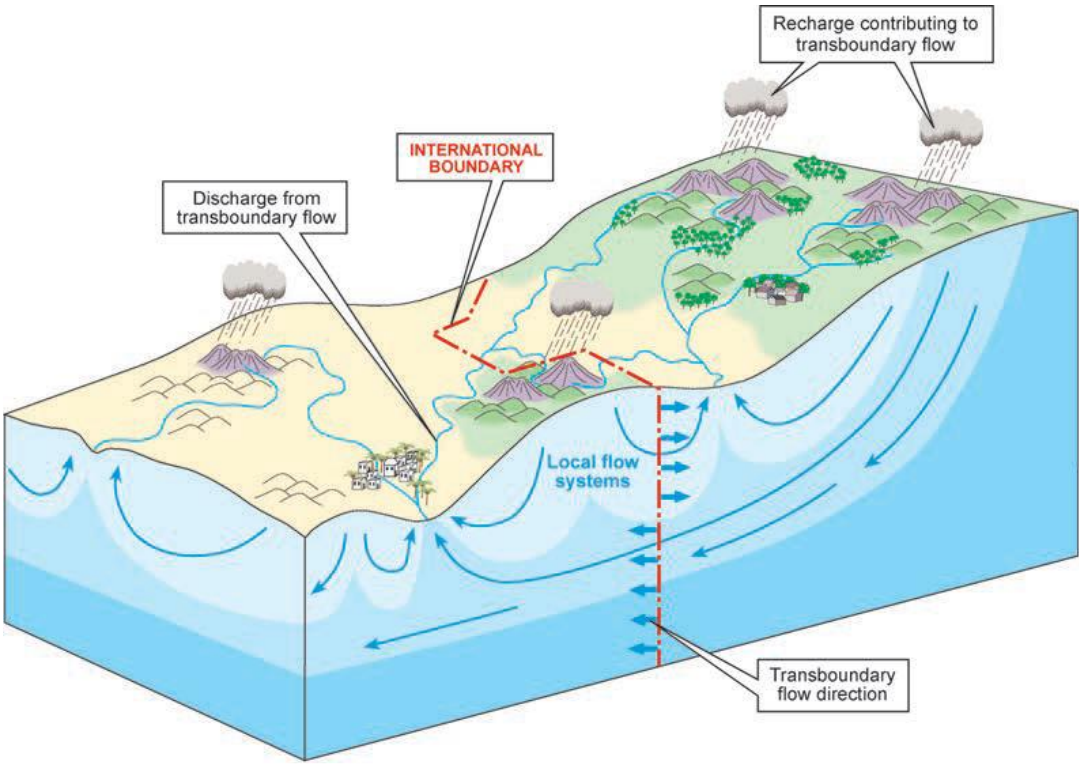


Figure 2.1 - A theoretical conceptual representation of a transboundary aquifer (Puri and Naser, 2003)

Figure 2.2 illustrates a series of transboundary aquifer scenarios (Eckstein and Eckstine, 2005). Hydraulic connections to surface waters and recharge/discharge zones can change the way a transboundary aquifer is defined and managed. Figure (a) represents a simple transboundary aquifer where groundwater moves from one state down-gradient to another state. This aquifer is not connected to surface water and thus is considered a 'fossil aquifer'. Once its stored groundwater has been abstracted, it cannot be replenished by recharge (Martin-Nagle, 2011). An example of this aquifer type is the Nubian Sandstone Aquifer shared between Libya, Chad, Egypt, and Sudan (LaMoreaux et al., 1985 and Sultan et al., 2004 in Eckstein and Eckstein, 2005). The addition of a river along the international border (b) creates a transboundary aquifer system where surface water and groundwater is hydraulically connected and now both transboundary groundwater and surface water must be managed together. Examples of this aquifer type are the Ruo Transboundary Aquifer System and the Shire River Basin Alluvial Aquifer, both shared between Malawi and Mozambique (ILEC et al., 2016 and SADC-GMI, 2018). This situation is complicated if the surface water crosses the border as depicted in scenario (c) as the considerations of upstream/downstream states need to be considered for both surface water and groundwater while being managed together as a system, for example in the Nile River Basin (NBI, 2016). Similarly, in scenario (d), although the surface water is domestic, it is still hydraulically connected to a transboundary aquifer and therefore still needs to be managed as a system. This is particularly an issue when trying to apply legal instruments designed for surface water management to the groundwater component as often, aquifer boundaries do not match surface water basins. An example of this situation is Mimbres Basin aquifer, a transboundary aquifer shared between northern Mexico and New Mexico that is recharged by the Mimbres River, which is a domestic river inside the boundary of the United States (Hebard 2000 in Eckstein and Eckstein, 2005).

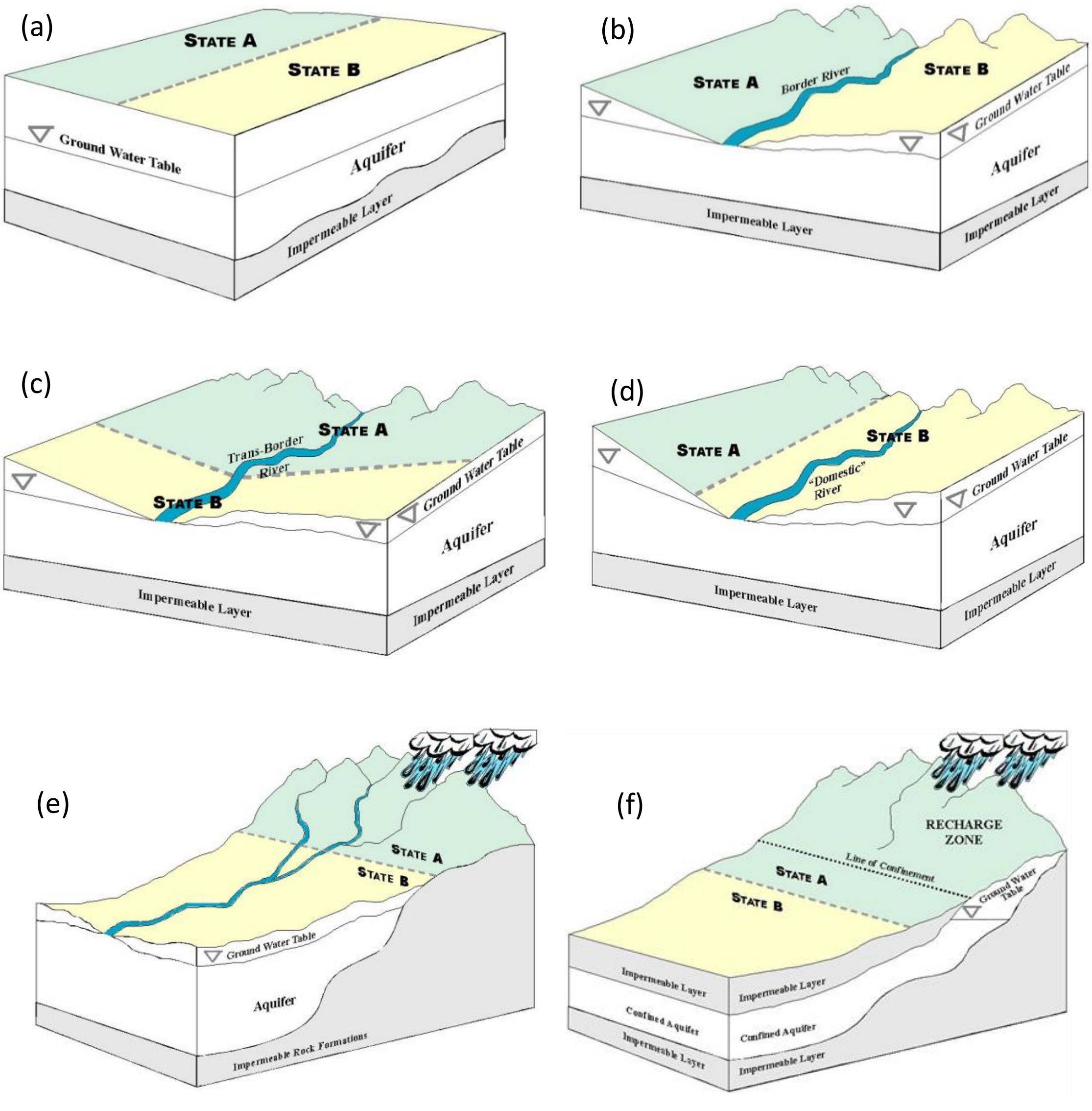


Figure 2.2 - A series of transboundary aquifer scenarios (Eckstein and Eckstein, 2005)

Scenario (e) illustrates a domestic aquifer that is fed by international recharge. In this case, although the aquifer is not transboundary, it still has a transboundary implication due to being connected to an international river and receiving recharge from out with the country border. An example of this scenario are the Euphrates rivers that have their headwaters in Turkey and feed a domestic sedimentary aquifer within Iraq (FAO AQUASTAT in Eckstein and Eckstine, 2005). Finally, scenario (f) shows a transboundary aquifer receiving recharge from only one state. Here, groundwater is primarily located in the downstream state however is being fed by the upstream state, such as in the Guarani Aquifer, that is 90% confined, shared between Brazil, Paraguay, Uruguay and Argentina that receives its recharge in Brazil (Matlala, 2017). These upstream/downstream interactions are important to consider in transboundary management. However, often the recharge and discharge components of transboundary aquifers are poorly understood.

The definition of a transboundary aquifer is fairly nuanced throughout the international community. First, within International Law, the general rule is that the borderline extends vertically into the sub soil. Subsequently, some could interpret this to mean that groundwater contained in storage beneath the ground could be regarded as the property of that country; This poses the crucial issue of the flowing component of transboundary aquifers (Llamas and Custodio, 2002). Subsequently, international water law has struggled to provide a way forward. Recently, the UN Draft Articles on the Law of Transboundary Aquifers (2008) tried to harmonise the definition of a transboundary aquifer through consultation of both scientists and policy makers (Eckstein, 2007). Within the articles, a transboundary aquifer is defined as “a permeable water-bearing geological formation underlain by a less permeable layer and the water contained in the saturated zone of the formation” (UN, 2008). The explicit inclusion of the water within the definition was seen as a compromise between scientists and policy makers (Eckstein, 2007). Under this definition, a portion of the aquifer today may not be part of the aquifer tomorrow as groundwater is often in constant flux. This definition also causes confusion when member states try to define the physical extent of the transboundary aquifer they wish to manage (Eckstein, 2007). In comparison, the EU Water Framework Directive (2002) opted to classify their shared groundwater resources as "Groundwater Bodies" defined as subdivisions of large geographical areas of aquifers (Dochartaigh et al., 2015). This was done in order to effectively manage groundwater in conjunction with surface water in a basin wide approach however it can cause difficulties when trying to understand the true extent of transboundary groundwater within European countries. The Convention on the Law of the Non-Navigational Uses of International Watercourses (New York, 1997) defines a transboundary watercourse as a system of surface water and groundwater that are hydraulically connected. Finally, the UNECE Convention on the Protection and Use of Transboundary Watercourses and International Lakes (UNECE Water Convention) defines transboundary water as any surface or ground waters which mark, cross or are located on boundaries between two or more states.

More recently, it has been suggested that even the extent of the geological unit and/or water contained within it is a redundant basis on which to define a transboundary aquifer. As certain areas of an aquifer are only often utilised, it is proposed that the delineation of the aquifer should be based on factors such as population density, active pumping areas, and density of active (Sanchez et al., 2020). Similarly, some have suggested that a certain distance from the border could be defined as the transboundary component of the aquifer (Eckstein, 2015). For the purposes of this research, the scientific and geological definition of 'transboundary aquifer' is adopted: A permeable water-bearing geological unit that has the ability to store and transmit groundwater.

2.3 Transboundary Aquifer Assessments

The importance of transboundary water resources has been understood since the 1970's (UN, 1978 in Wolf et al., 1999). International river basins were extensively studied due to their potential for conflict (Westing, 1986; Gleick, 1993; Homer- Dixon, 1994; Remans, 1995; Samson and Charrier, 1997 in Wolf et al., 1999). Small cases of transboundary groundwater assessments and cooperation were seen in Northern African at this time, primarily the Nubian Sandstone Aquifer System and the North Western Sahara Aquifer System due to their strategic importance (NSAS 2002, SASS

2002 in Eckstein. 2011). However, it was not until the International Hydrological Programme (IHP) of the United Nations Educational, Scientific and Cultural Organization (UNESCO) established the Internationally Shared Aquifer Resources Management Initiative (ISARM) in 2000 that transboundary groundwater gained more international recognition (Rivera and Candela, 2018). The International Groundwater Assessment Centre (IGRAC) was then set up in 2003 when UNESCO and the WMO took the initiative to establish an international groundwater resource assessment centre that was to particularly focus on transboundary aquifer assessment and groundwater monitoring (https://www.un-igrac.org/).

Since its formation, ISARM has launched a number of global and regional initiatives. These include: the 'Assessment of Transboundary Rivers, Lakes and Groundwaters'; the 'Global Environment Facility Transboundary Waters Assessment Program' (GEF-TWAP); the establishment of four regional ISARM networks of experts to identify, map and manage transboundary aquifers; a global inventory and a global map of TBAs; and assisting in the drafting of the UN Draft Articles on the Law of Transboundary aquifers (UNECE, 2011; ILEC et al., 2016; Rivera and Candela, 2018; IGRAC and UNESCO-IHP, 2015b.) IGRAC also publishes a 'Transboundary Aquifers of the World' map with all known TBAs displayed based on the most recent inventory results from many projects globally. This compilation of all international data constitutes a valuable starting-point for governments. There are 592 TBAs currently identified worldwide. Half of these are shared within European Member States and identified as part of the Water Framework Directive requirements. A further 80 of these are located within Africa (IGRAC and UNESCO, 2015a; IGRAC and UNESCO, 2015b) accounting for 43% of the continental land surface (Altchenko and Villholth, 2013). TBA assessments internationally have been largely focused on the regional scale (ILEC et al., 2016; Rivera and Candela, 2018). A large proportion of TBAs within Africa were identified through the GEF-TWAP regional assessments (ILEC et al., 2016). The aim of the GEF-TWAP was to provide the first global scale assessment of all transboundary waters. GEF-TWAP regional assessments were carried out by an appropriate representative from each country and then collected and streamlined by the project (ILEC et al, 2016).

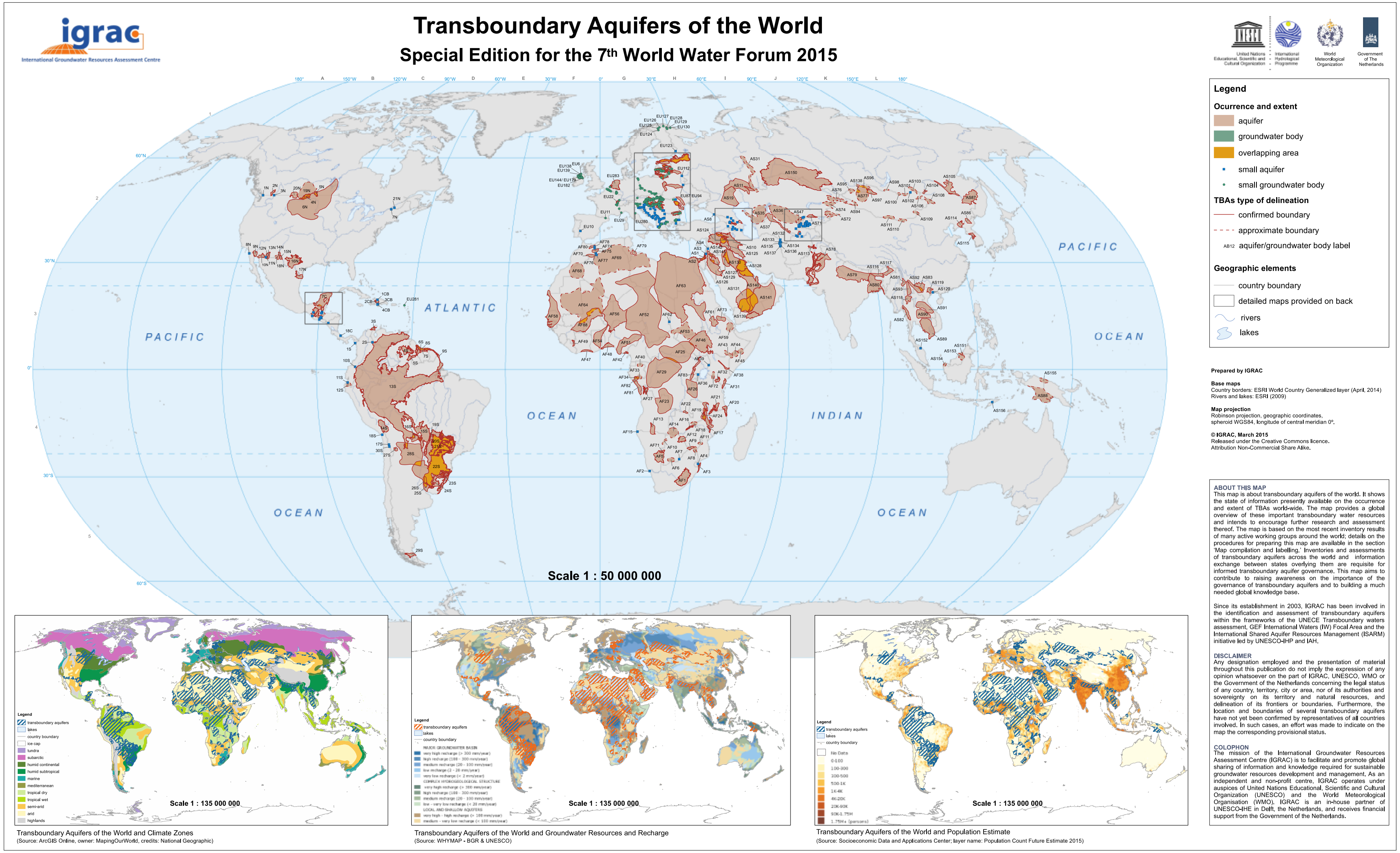


Figure 2.3 - Transboundary Aquifer Map of the World (IGRAC and UNESCO-IHP. 2015b)

Many individual countries are now recognising the importance of TBA identification as a contribution to IWRM and more recently, the achievement the SDGs (European Commission, 2015; Puri & Aureli, 2005; Zektser, 2010). They are assessing key TBAs, most often identified through regional initiatives. However, these aquifer systems are laterally extensive and this mode of assessment may fail to resolve the potentially more local transboundary issues where more local minor aquifer assessments become more valid. In contrast, individual TBA system assessments are more common (Petre et al., 2016; Petre et al., 2015). Such dedicated aquifer system-focused assessments, whilst critical, do not represent the whole transboundary circumstances of a country. Such detailed assessments also require extensive data and financial resources that may not be available to many developing countries. There is a need for countries to develop a TBA assessment strategy that systematically screens its entire national border at relevant scales. This will then allow for identification of a country's groundwater resources that are most vulnerable to TBA influence and cross-border flows. These issues are further explored in chapter 4 and 5.

A recent push for further transboundary aquifer assessment and management has come in the establishment of a newly elected Transboundary Aquifer Commission supported through the International Association of Hydrogeologists. The scope of activities of this commission will include; (1) continued assessment of TBAs (2) redefining the nature of transboundary aquifers, transboundary groundwater, and conceptual models (or frameworks) (3) creating a standardised nomenclature for TBAs and (4) promoting and developing studies for sound management and governance of TBAs (IAH Commission on Transboundary Aquifers, 2020a).

Recently, members within the commission have called for more research to be undertaken on how to zone or prioritise specific areas of transboundary aquifers for more directed management. It is proposed that when dealing with a large number of TBAs or a laterally extensive TBA, only specific areas may require detailed assessment or an arrangement to manage them. However, methodologies to support this approach are limited (IAH Commission on Transboundary Aquifers, 2020b). This topic is explored further in chapter 6.

2.4 Transboundary Aquifer Governance

Strong governance is required to ensure transboundary cooperation and management (Linton and Brooks, 2011). Transboundary groundwater is, however, an area of international law that has been underrepresented (Matsumoto, 2002). Though transboundary surface water governance is regularly practiced nowadays, transboundary groundwater governance has received comparatively little attention to date (Eckstein, 2015). Out of 592 TBAs identified worldwide, there are only 6 full agreements currently in place (i.e. treaties signed by the Aquifer States): The Genevese Aquifer Agreement (France and Switzerland) (1977 & 2007); the Regional Strategic Action Plan on the Nubian Sandstone Aquifer (Chad, Egypt, Libya and Sudan) (1992 & 2000); the Guarani Aquifer Agreement (Argentina, Brazil, Paraguay and Uruguay) (2010) and the Al-Sag/Al Disi Aquifer Agreement (Jordan and Saudi Arabia) (2015); the North West Sahara Aquifer System Memorandum of Understanding: (Algeria, Libya and Tunisia) (2002-2008) and the Lullemeden Aquifer System Memorandum of Understanding: (Mali, Niger and Nigeria) (2009) (Burchi, 2018). This is minor in comparison to over 3,600 treaties relating to the use of transboundary surface waters (UNEP, 2002; cited by Eckstein and Sindico, 2014). This focus on surface water transboundary resources is also evident through the structures of River Basin Organizations and Watercourse Commissions that continue to align themselves with surface water catchments, often side-lining the conjunctive relationship between surface and groundwater.

The European Union has been progressive in its effort to regulate and manage transboundary resources. The EU Water Framework Directive (WFD) was published and entered into force due to increasing demand for cleaner and more sustainable rivers, aquifers, lakes and beaches. Its main purpose was to set objectives for the protection of water bodies for the future (European Commission, 2015) and to promote an integrated water resource management approach. It calls for all member states to take responsibility for their inland and costal water bodies achieving a “good status” or better (DAERA, 2019). To achieve this, member states must establish integrated basin level water management and publication of river basin management plans that set out a management agenda for six-year time frame cycles (2009-2015, 2016-2021 and 2022-2027) (DAERA, 2019; European Commission, 2015; Daly, 2016). These plans outline the approach each member state will take to ensure each water body reaches good status in terms of both water quality and quantity (European Commission, 2015).

Article 5 of the WFD requires member states to also characterise all aquifers within respective River Basin Districts. The EU Water Framework Directive is the only piece of legislation worldwide that asks all member states party to it to identify, assess and manage their shared groundwater resources at the national and local scales. This assessment includes identification of aquifer extent, location and all influencing pressures and risks that are relevant to them. This is done by first classifying the geology along the border region according to physical aquifer and groundwater chemistry properties. Aquifers are then delineated across the border in cooperation with neighbouring countries. Both bedrock and superficial aquifers are included within the assessment (Dochartaigh et al., 2015).

There are currently three international legal instruments available for countries that wish to foster a transboundary groundwater agreement. The Convention on the Law of the Non-Navigational Uses of International Watercourses (UNWC) entered into force in 2014 (UN, 2014). It is a global treaty that addresses transboundary watercourse agreements for countries that have ratified it. This convention applies to all international watercourses and their waters, and specifically to this case, to transboundary groundwater aquifers that are hydraulically connected to surface waters (Article 2). The convention is based on the concept of ‘equal and reasonable utilization’ thus entitling watercourse states to equal rights to the utilization of the watercourse (Article 5). Under the convention, states are also required to not cause significant harm to the watercourse (Article 7). States are also obliged to share data relevant to the watercourse regularly with each other (Article 9) to preserve dependant ecosystems of the watercourse (Article 20) and manage pollution and/or contamination (Article 21) (UN, 2014). The Watercourse Convention is however not a complete inclusive representation of the status of groundwater within international law. The convention was never created with the purpose of covering all aspects of groundwater international law within its scope. Subsequently, its criteria as to whether a transboundary aquifer is within its scope is not inclusive of all potential transboundary aquifer circumstances (Eckstein, 2007). For example, aquifers that are not hydraulically connected to surface water systems but which may still transmit water across international boundaries are not under the Watercourse Convention (Rieu-Clarke et al., 2013). Non-renewable groundwater sources and aquifers that are not connected internationally through surface waters or river basins are not considered to be part of this convention (Eckstein, 2007). The Watercourse Convention does not have a standard definition of what constitutes a transboundary aquifer alongside its suggested criteria for the management of these resources. These are considerable limitations of this convention.

The second legal instrument available is the UN Draft Articles on the Law of Transboundary Aquifers (UN, 2008). The UN Draft Articles on the Law of Transboundary Aquifers were published in 2008 after a brief 6-year development initiated in 2002 by the UN International Law Commission. They are currently annexed to a UN General Assembly Resolution and are non-legally binding. Subsequently, the Draft Articles can only provide guidance for countries who which to utilise them to assist in the development of a transboundary aquifer agreement. The Draft Articles are intended to provide guidance to member states when the Watercourse Convention does not (Sanchez et al., 2016). This set of Draft Articles differs to the Watercourse Convention in that they solely focus on groundwater/groundwater systems (Article 2a). For an aquifer to fall under the governance of the Draft Articles, it must cross a political border or have a hydrological connection within another country/state (thus the Draft Articles extend to all surface waters connected to transboundary aquifer). The articles focus on the use of transboundary aquifers/aquifer systems and other activities that may impact said aquifers/aquifer systems and encourage measures to protect and manage them (UN, 2008). The articles promote equitable and reasonable use (Article 4), regular exchange of data (Article 8), the identification of recharge and discharge zones (Article 11) alongside cooperative system monitoring (Article 13) and implementation of measures to do no significant harm (Article 12). It should be noted that the Draft Articles and other legislative options can be mutually supportive (Allan et al., 2011; UNECE, 2014). The definition of the term "aquifer" within the Articles is unique and was seen as a compromise between policy makers and scientists. Traditionally, an aquifer is a geological unit with the ability to store and transmit water. However, the Articles consider the aquifer as both the geological unit and the water that is stored within it. Under this definition, a portion of the aquifer today may not be part of the aquifer tomorrow as groundwater is often in constant flux. This definition may cause issues when countries use the Articles to try to define the physical extent of the transboundary aquifer they wish to manage (Eckstein, 2007).

Finally, a third legal instrument is the UNECE 1992 Convention on the Protection and Use of Transboundary Watercourses and International Lakes (UNECE Water Convention) and its accompanying Model Provisions on Transboundary Groundwaters (UNECE, 2013; UNECE, 2014). The Water Convention was originally negotiated as a regional framework for the Pan-European region. In 2013 it was then amended and in 2016 it was opened up for accession to all UN Member states (Sindico, 2020). The Water Convention does not replace bilateral agreements between countries but instead fosters their establishment and implementation. It calls for parties to prevent, control and reduce their transboundary impacts (Article 2), regularly exchange information (Article 6), conduct joint monitoring and assessment (Article 11) and ensure reasonable and equitable utilization of transboundary water amongst other provisions (UNECE, 2013). The model provisions provide guidance on how to fulfil these provisions within a bilateral or multilateral agreement specifically for transboundary aquifers and were designed to build upon and work alongside the aforementioned Draft Articles (UNECE, 2014).

Often, transboundary aquifer governance is undertaken at the institutional level. Specific examples include: River Basin Organizations such as The Zambezi Watercourse Commission (ZAMCOM) and the Orange-Senqu River Commission

(ORASECOM) that have groundwater management commitments within their mandate (SADC-DW/ Zambezi River Authority, 2008; Nijsten, 2018); the Southern African Development Community Water Division’s Regional Water Strategy that provides a strategic framework for sustainable use, protection and control of both national and transboundary water resources within the region; the implementation of the Revised Protocol for Shared Watercourses (2000) that aims to foster close cooperation between member states over their shared water resources (SADC, 2003); and the recent creation of the SADC Groundwater Management Institute that is based in South Africa and aims to support the sustainable management of groundwater at national and transboundary levels across SADC member states (SADC-GMI, 2016).

The discussed legal and institutional mechanisms are designed for international and regional applicability. Management of TBAs at the national and local level however, is still within its infancy. Out with the WFD, there is no legal mechanism that asks countries to assess and manage all of their transboundary aquifer at relevant scales.

2.5 Sustainable Development Goals

The international monitoring of drinking water and sanitation has been on-going since the 1930s (figure 2.4). Subsequently, the global water and sanitation landscape has changed dramatically including the creation of policies, national initiatives and new technologies. However, this has gone in hand with a high increase in population, doubling since 1970. In 2000 the Millennium Development Goals were adopted by the UN’s general assembly member states (UNGA, 2000). Although considered a vital human right and fundamental to livelihood, health and economic development, water was not given its own goal. It was included in Goal 7, ‘Ensure Environmental Sustainability’. The water related target of Goal 7 was to “halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation”. However, by the end of the Millennium Development Goals, there was still 663 million people across the globe without access to an improved supply of water. Half of these people were living in Sub-Saharan Africa (WHO and UNICEF, 2015).

The Sustainable Development Goals superseded the Millennium Development Goals in 2016. Water was given its own goal. SDG 6 expands the Millennium Development Goal focus on drinking water and basic sanitation to include the management of water and wastewater and ecosystems, across boundaries of all kinds. The overall goal is ‘to ensure availability and sustainable management of water and sanitation for all’ (UN, 2017) however it has 8 specific targets.

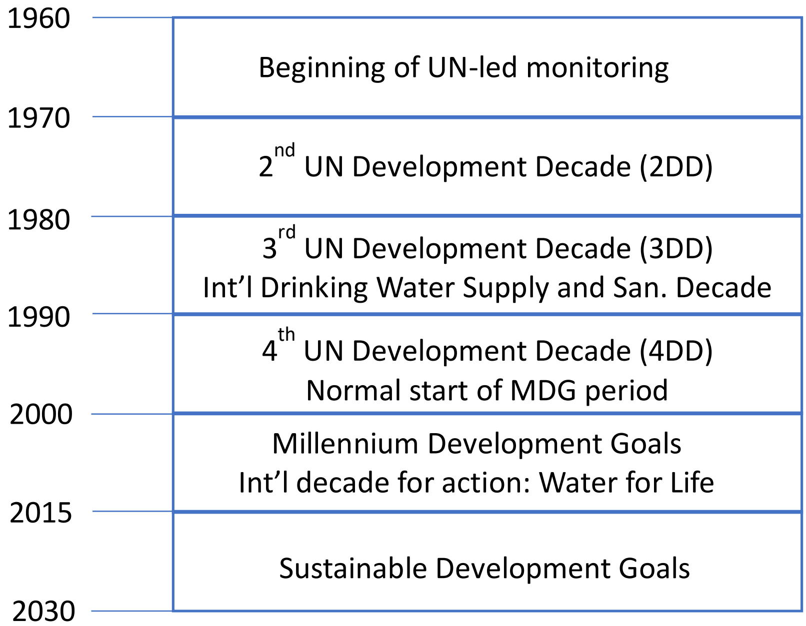


Figure 2.4 - Timeline of international targets and actions related to drinking water and sanitation (Bartram et al., 2014)

The importance of transboundary water management has been recognised within the Sustainable Development Goal agenda. Target 6.5 of Goal 6 specifically refers to transboundary water management; “by 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate” (UN Water, 2015). In order to track and measure the progress of SDG 6, Target 6.5, all UN member nations are asked to report on two separate indicators; 6.5.1 – The degree of integrated water resources management implementation (0-100) and, 6.5.2 – The proportion of a transboundary basin area with an operational arrangement for water cooperation. UNESCO led the development of a methodology to calculate indicator 6.5.2 alongside co-custodians for the indicator, UNECE. The methodology calls for the proportion of a transboundary basin/aquifer area with an operational arrangement for water cooperation within a state to be calculated (UN Water, 2020a) and results are presented by country as a percentage.

The calculation of the indicator 6.5.2 is based on (UN Water, 2017a):

a) The total surface area of a transboundary river/lake basin or aquifer within a country;
b) Whether any part of the basin/aquifer is covered by an arrangement for water cooperation; and
c) Whether that arrangement is operational.

The term 'operational' requires any arrangement to have the following 4 criteria in place in practice (UN Water, 2017a):

(1) There is a joint body, joint mechanism or commission (e.g., a river basin organization) for transboundary cooperation
(2) There are regular (at least once per year) formal communications between riparian countries in form of meetings (either at the political or technical level)
(3) Joint objectives, a common strategy, a joint or coordinated management plan, or an action plan have been agreed upon by the riparian countries
(4) There is a regular (at least once per year) exchange of data and information

The reporting for SDG 6.5.2 is undertaken in conjunction with reporting under the Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Water Convention) and first took place in 2017 (UNECE, 2020a; UNECE, 2018). National level reporting for both is therefore done through a single template every 3 years (UNECE, 2020a; UN Water, 2017b). Joint reporting offers countries a way to assess the extent that their current progress on transboundary cooperation is aligned with the Water Convention, allowing comparison of practices with the experiences of the Parties to the Convention (UNECE, 2020a). The reporting template also allows stakeholders to see a figure picture of the progress under SDG 6.5.2 that the simple indicator alone offers; for examples, it allows understanding of what ways a county may not be achieving an operational agreement (UNECE, 2020a). The reporting template is broken down as follows:

- Section 1: data to calculate the value of SDG indicator 6.5.2.
- Sections II to III: aspects of reporting relevant to the implementation of the Water Convention
- Section IV: summarizes the key challenges and achievements in transboundary water cooperation

Although reporting is done at a national scale, theoretically, the status of a transboundary aquifer should be identical for all countries involved. However, this is not always the case in the reporting, suggesting that there can be different levels of what operational cooperation is considered within the basin (UN Water, 2017b) In order to assist countries with the reporting process, technical support and capacity building workshops have been carried out across regions and sub-regions (UNECE, 2021).

The most recent progress report for SDG 6.5 does not paint an optimistic picture for the achievement of the target. Implementation of IWRM within countries is around 40% with another 40% claiming adoption of IWMM elements and implementation is underway. The final 19% of countries have only just started to develop some elements of IWRM. Subsequently, 60% of countries are currently at risk of causing negative environmental, social and economic impacts through mismanagement of their water resources (UN Environment, 2018). The outlook of the transboundary component of IWRM is even more bleak. Approximately three quarters of countries with shared waters report that they have established some form of agreements, organizational frameworks, data sharing and financial arrangements for transboundary water management (UN and UNESCO, 2018). However, the degree of implementation, or operationalization, of these aspects varies greatly. Only 17 countries hit the target and have all their transboundary basins covered by operational arrangements. In total, there is 59% coverage worldwide for this target. However, when looking at transboundary aquifers specifically, the coverage is 48%, even lower than the overall indicator (UN and UNESCO, 2018). These estimates are also likely to be optimistic because countries have been asked to report only on the status of transboundary water management for the majority of what they consider to be their most significant transboundary basins and aquifers.

Furthermore, countries are only able to report on known transboundary aquifers and it is likely that there are many more unidentified transboundary groundwater resources shared internationally. The results from 6.5.1 and 6.5.2 reporting both suggest that a significant effort is needed to strengthen both transboundary waterbody identification and cooperation (UN and UNESCO, 2018). Research is therefore needed to identify and assess more transboundary aquifers alongside gathering sufficient data to establish operational transboundary arrangements between countries in order to meet SDG 6.5. This must be done at all levels (regional-national-local).

In addition to the main targets set under SDG 6, two additional implementation targets have been created under the understanding that, although the implementation of SDG 6 is expected to generate benefits that widely exceed the costs of doing so, in some regions, needs are greater and financial recourses are more limited (UN Water, no date). Over 80 per cent of countries from a 2016-2017 GLAAS survey said they had insufficient funding to reach national targets on drinking water and sanitation (UN Water, 2017b). Alongside this, the IWRM Status Report (2012) reported that only 38 per cent could report on an “advanced stage” of stakeholder engagement implementation (UN Water, 2017b).

SDG Target 6.a and 6.b call for increased mobilization of funds and support available to developing countries in order to achieve their targets. WHO, UN Environment and IECD are the target custodians (UN Water, 2017b). These “means of implementation” targets are also complimentary with SGD Goal 17 “strengthen the means of implementation and revitalize the global partnership for sustainable development” (UN Water, no date, UN Water, 2017b). Specifically, Target 6.a states:

“By 2030, expand international cooperation and capacity building support to developing countries in water- and sanitation-related activities and programmes, including water harvesting, desalination, water efficiency, wastewater treatment, recycling and reuse technologies” (Guppy et el., 2019; UN Water, 2015). Here, international cooperation is seen as aid in the form of grants or loans and the target indicator is measured as the amount of water and sanitation related official development assistance that is part of a government-coordinated spending plan (Guppy et al., 2019). Target 6.b is focused on the increased participation of local communities to meet the need of the SDGs; essential in order to ensure the needs of local communities are being met. (UN Water, 2017b). Specifically, Target 6.b states:

“By 2030, Support and strengthen the participation of local communities in improving water and sanitation management” (Guppy et al, 2019; UN Water, 2015)

6.b is measured as the proportion of local administrative units within a country with operational policies and procedures for the participation of local communities in WASH management (Guppy et al., 2019). Including stakeholders at the local level gives communities’ ownership over their water and sanitation which is tern can lead to longer term and more sustainable progress and management. This target is also directly linked to SDG 6.5 that called for IWRM at all scales, including the local level (UN Water, 2017b).

2.6 Regional Context

The primary case study for this research is Malawi, a small country in south east Africa. Africa is a continent challenged by limited water supply, poor quality of living, and economic uncertainty. The SADC was established in 2004 to bring together countries within the south-eastern African continent to improve living situations for large populations of people. Malawi, one of the 15 countries within the SADC, lies between 9^{o}S and 17^{o}S (latitude) and 33°E and 36°E (longitude). It extends across an area of 118,484 km^2 stretching 853 km N – S and 257 km E – W (Chavula, 2012). Lake Malawi covers 23.6% of the country, the third largest freshwater lake in Africa. Malawi’s population is estimated to be 18.3 million (Worldometers, 2017) of which

90% live in rural areas. Its main economic income is generated from agriculture, with subsistence farming common amongst the rural population (Government of Malawi, 2012). With less than 1,400 m^3/year/person of available total renewable water resources, Malawi is one of the most water-stressed countries in the world (Government of Malawi, 2012). This is largely due to the lack of infrastructure within the country to support large-scale management of water resources and much of its rural population accessing groundwater through hand-dug wells or low-capacity boreholes fitted with hand pumps. With the population of Malawi set to rise to 26.5 million by 2030 and renewable water resources likely to decline due to deforestation and climate change impact, Malawi could become water scarce with available total renewable water falling below 1000 m^3 /year/person in the next 13 years. These valuable groundwater resources are vulnerable to pollution threats that may be poorly constrained (Back et al., 2018). Sparse monitoring of both groundwater quality and level can also lead to a poor knowledge base for management (Rivett et al., 2018a). Such factors, and others, indirectly influence the strategic development of TBA assessment and management within the country (Rivett et al., 2018b).

Malawi was selected as the primary case study for this thesis due to multiple reasons. As discussed, many people across Malawi heavily on groundwater for their livelihood, particularly in rural areas (Chavula, 2012; Kalin et al., 2019). Logically, a proportion of this groundwater will be shared transboundary. Although vastly important, many groundwater resources are still poorly understood in Malawi (Rivett et al., 2018a). Specific characteristics including aquifer thickness, depth to water table, recharge and discharge zones, connectivity to surface waters, groundwater flow direction, groundwater contamination, natural groundwater quality etc. are either not reported or poorly understood to an appropriate level for sustainable management (Back et al., 2018; Kalin et al., 2019; Smith-Carrington and Chilton, 1983). This makes the challenge of identification and descriptions of transboundary aquifers challenging. Malawi also has a range of aquifer types (sedimentary, igneous and basement (Smith-Carrington and Chilton, 1983), allowing for a range of management structures to be explored. Furthermore, although widely recognised that groundwater is an integral part of many hydrological systems, many IWRM approaches adopted within Malawi still omit transboundary groundwater from their scope (Smith-Carrington and Chilton 1983). Furthermore, although Malawi's national water policy is well developed, its implementation across the country is limited. For example, the Malawi Water Resource Act (2013) requires licenses for groundwater abstraction to be obtained however in practice, this is often not the case (Kalin et al., 2019). Although the national legal and institutional context of Malawi are relevant, the focus is only on transboundary governance. Recognition of the problems in relation to Malawian national water governance, and its importance with respect to the implementation of international agreements are acknowledged, but are a general issue beyond the scope of this thesis.

Malawi also posed an interesting study area due to its geographical position as a landlocked country, thus having multiple transboundary neighbours. Finally, Malawi is party to the SADC Protocol on Shared Water Resources and the Zambezi Commission, suggesting that there is at least some mandate for cooperative management of their transboundary aquifers (SADC-DW/ Zambezi River Authority, 2008). Overall, Malawi can also be considered representative of many countries worldwide that have limited access to financial resources and technical expertise.

3 Methodology

The thesis is developed as a series of papers published in peer-reviewed journals. This chapter highlights the research philosophy adopted, main materials and methodologies used throughout the research, and highlights the standing of this thesis within the wider Climate Justice: Water Futures programme.

3.1 Research Philosophy

In order to address the research objectives identified in section 1.2.2, a pragmatic empirical approach was adopted (Ormerod, 2006; Kaushik and Walsh, 2019). Both qualitative and quantitative research methods were employed using inductive and deductive reasoning (Cresswell and Clark, 20011; Tashakkori and Teddlie, 2010; Thomas, 2006). A mixed and a multi-method design was utilised at various stages of the research (Lewis-Beck, 2004). This research design allowed for multiple stand-alone research projects and thus different methodological approaches (delineated in detail in individual chapters) that are then aggregated by an overall aim (Morse, 2003; Teddlie and Tashakkori, 2003). It also allowed for flexibility as the research progressed allowing for adaption as and when new data or ideas were generated. This research design is particularly effective when dealing with multidisciplinary research, as in this thesis.

3.2 Climate Justice Fund

This PhD is embedded within a larger research programme, called the Climate Justice Fund: Water Futures Programme (CJF), that was awarded to Professor Robert Kalin (Principal investigator and PhD supervisor) by the Scottish Government in 2011. The aim of the programme is to assist the Government of Malawi to achieve Sustainable Development Goal 6: Water and Sanitation for all. The programme was split into 4 key work streams; Asset Management, Policy Exchange and Support, Capacity Building, and Research and Knowledge Exchange. This PhD thesis fits into the Research and Knowledge Exchange work stream. One of the major deliverables from the programme was the creation of a Management Information System to allow for the asset management of water points, sanitation points and waste sites (Kalin, 2019). Data were collected through a series of water point functionality and household level surveys. Information gathered included water point functionality, geographical location, accessibility, reliability and communities served. In total, 120,935 water points, 278,045 sanitation points and 10297 waste sites were assessed with 5 pieces of site data per water point collected, 81 questions per Water Point Functionality Survey asked and up to 23 questions per Sanitation Survey asked. mWater (www.mwater.co), was selected as the platform used to collect and host the dataset generated. This 'big dataset' was utilised within this thesis in chapter 7.

The research from this thesis has informed other research projects under The CJF (Kalin, 2019; Banda et al., 2020, Kelly et al., 2020). Similarly, other research from the programme is referenced within this thesis (including Truslove et al., 2020; Kalin et al., 2019; Rivett et al., 2018a and b; Rivett et al., 2019).

3.3 Research Materials

This thesis utilised a variety of research materials, each described below.

3.3.1 Geological and Hydrogeological Maps

Geological and hydrogeological maps in pdf format were acquired from the Geological Society of Malawi, the Geological Survey Department of Zambia and the Geological Survey or Tanzania (Geological Survey of Malawi, 1970; Ferro & Bouman, 1987a and b; Geological Survey Department of Zambia, 1975; Deltares and Aurecon, 2016; Geological Survey of Tanzania, 1953)

3.3.2 GIS Shapefiles

GIS shapefiles were obtained from the open source Malawi Spatial Data Platform (MASDAP), The Malawian Government and the British Geological Survey (BGS) (Persits, 2002; Upton et al., 2018; MASDAP, 2019). These shapefiles included digital data on border delineation, land use, geology and hydrogeology.

3.3.3 CJF mWater Dataset

The CJF mWater dataset (stored on the mWater platform, www.mwater.co) was used in chapter 7 of this thesis. It is comprised of data from over 120,935 water points, 278,045 sanitation points and 10297 waste. It also included data from an 81-question Water Point Functionality Survey and a 23-question Sanitation Survey.

3.4 Research Methods

This thesis utilised a variety of research methods in order to achieve its objectives. Each is described below.

3.4.1 Literature Analysis and Review

A literature analysis method was used in chapters 2, 4, 5, 6 and 7 of this thesis. Available data and literature was gathered and critically assessed using an integrative approach (Synder, 2019). An integrative approach was selected due to its ability to allow new theoretical frameworks and perspectives to emerge through the review process. It is also a useful approach for newly emerging topics, like transboundary groundwater management, allowing for the creation of initial conceptualizations and theoretical frameworks rather than a review of old models (Torraco, 2005; Synder, 2019). Online databases such as Scopus, Google Scholar and Mendeley were utilised by searching for key phrases such as “transboundary aquifers”, ‘transboundary aquifer management”, “transboundary aquifer assessments” and “regional transboundary aquifer assessments and management”.

3.4.2 Transboundary Aquifer Delineation

The GIS software QGIS (version 3.4) was used in chapters 4 and 5 of this thesis for map correlation. Hydrogeological and geological maps were imported into QGIS and georeferenced. These maps were then harmonised across the international border of Malawi by matching geological and hydrogeological units across the maps and presenting them as single continuous units. Harmonised geology and hydrogeology units were used to identify water bearing units (aquifers) that cross international borders. Upon identification, new shapefiles of these units were created which were presented on a map. Hydrogeological characteristics of each aquifer were then identified including lithology, surface area extent, productivity, potential surface water connections, water quality and finally, groundwater flow direction using piezometric surface maps.

3.4.3 Fuzzy Logic Hotspot Analysis

Spatial analysis of transboundary aquifers in Malawi was undertaken using fuzzy logic and GIS overlays to generate 'hotspot maps' of areas with the greatest risk of transboundary miss-management in chapter 6. The hotspot map is generated using multiple input raster layers that each have weighted attributes attached to them based on the parameter being modelled, which is then summed to produce a combined raster layer. The higher the cell weight, the worst the case. From this, a heat map is produced highlighting the areas where the highest accumulation of highly weighted categories are shown as "hotspots". This hotspot spatial analysis was undertaken using 6 combined raster files. Each data point within these 6 files were given a weighting between 0 and 1 based on a selected criterion. The higher the weight, the worse the case and thus the higher the risk rating. The parameters selected for this case were – water point type, hydrogeology type, no. of users per water point, proximity to pit latrine, land use, seasonal fluctuations. Once combined, the cumulative weighting of each data point was calculated and was given within a range of 0 to 6. This overall weighting was then presented spatially in QGIS (version 3.4). Upon generation of the hotspot map, shapefiles of the known transboundary aquifers in Malawi were overlaid and eliminated based on their local or national hotspot significance. If a hotspot spanned across the majority of a transboundary aquifer, the hotspot was deemed to be of a national scale. If the hotspot was only focused along the border, then it was considered to be a local scale hotspot. Hotspots that were out with the limits of transboundary aquifers within Malawi were not considered within this study. Similarly, hotspots that are within a transboundary aquifer but not located near the border were not considered a current transboundary risk. Results were then presented spatially in QGIS (version 3.4).

3.4.4 Field Data Collection

New data was generated for chapter 7 of this thesis. This was done through a field work campaign. A complete risk assessment was approved in preparation for travelling to Malawi and conducting field work (see Appendix A). The district of Mulanje in Malawi and Milange in Mozambique were selected as the field site due to its easy access from the field base of Blantyre in Malawi and because it was identified as a hotspot of concern from analysis conducted in chapter 6.

Field work involved the collection of water samples from groundwater (community water supply boreholes) (19), hand-dug shallow wells (5) and surface water sources (rivers (12)). Sample sites were selected randomly. The following field constituents; Temperature, pH, Total Dissolved Solids (TDS), Turbidity and Electrical Conductivity (EC)), were measured onsite using a portable multimeter (Model: HI-98194, Hannah Instruments, Woonsocket, RI, USA). Besides, geographic information such as GPS coordinates and elevation were captured alongside well depth and water point functionality for groundwater points. All the 34 water samples collected were subjected to hydrochemical and stable isotopic analysis at the MoIWD National water laboratory. Isotope samples were collected in specialised bottles for δ18O and δD. A pair of acidified and nonacidified samples were collected from each sampling point using polyethylene bottles rinsed with deionised water prior to water sampling. The set of acidified sampling bottles was prepared using hydrochloric acid (HCl-20%) for cations (sodium as Na+, potassium as K+, magnesium as Mg2+, calcium as Ca2+ and iron as Fe2+) analysis, while the non-acidified set was meant for anions (carbonate as CO32− and bicarbonate as HCO3−, nitrate as NO3−, sulphate as SO42−, chloride as Cl−) analysis. The water samples were tagged with location identifiers using water-proof stickers for proper chain of custody. While in the field, the samples were kept refrigerated at 4 degrees Celsius in specialised field cooler boxes and transported to the MoIWD laboratory where temperature conditions were maintained. The water samples were filtered at the laboratory using 0.45µm filter membranes, also kept refrigerated (at 4 degrees Celsius) and away from direct sunlight to prevent photochemical decomposition before analysis.

3.4.5 Geochemical Analysis

Water samples from the field work campaign were analysed for broad geochemistry. The following constituents; CO_3^{2-} and HCO_3^- were determined by standard hydrochloric acid titration method, whereas Mg^{2+} and Ca^{2+} were determined by standard EDTA titration method and Cl^- was determined by standard silver nitrate method. A flame photometer (Model: 410, Camlab, Cambridge, UK) was used to measure Na^+ and K^+ based on flame photometry method, while an Ultra Violet (UV)/visible spectrophotometer (Model: DR/3000, Hach, Loveland, CO, USA) was used to measure NO_3^-, SO_4^{2-} and Fe^{2+} based on calorimetric and spectrophotometry method. The quality of the analysis process was assured and controlled by use of standard blanks and duplicate samples and calibration of all instruments per standard instructions prior to both field and laboratory analyses. Accuracy of the analysis results was validated by calculation of ion-balance in compliance with an acceptable error of ±5%. All field and laboratory activities (onsite measurements, sample collection, transportation, holding, preparation and analysis) were conducted in accordance with International Standard Methods (ISM) (APHA, 2012).

3.4.6 Isotopic Analysis

Water samples from the field work campaign were analysed for isotope markers. δ18O and δD were analysed using a Picarro isotopic water analyser (Model: L2110-I, Picarro, Santa Clara, CA, USA) at MoIWD Isotope Hydrology Laboratory based on a laser spectroscopy method following international standard methods (IAEA, 2009]). The water isotope samples were stored at 4 degrees Celsius, away from direct sunlight during transportation and holding at the IHL to prevent evaporative fractionation. The Picarro isotopic water analyser was calibrated daily using heavy and light standards spanning expected isotopic composition range of the water isotope samples. Daily control mid-range standard intermediate between heavy and light standards were used for further calibration. The precision (2σ) of the isotopic analysis was set at ±0.2‰ for oxygen-18 and ±2.0‰ for deuterium, while the isotopic analysis results were quantified and validated using a Laboratory Information Management System software specific for the Picarro isotopic water analyser. The results were reported in delta values (δ) that represent parts per thousand deviations (‰) from the international V-SMOW (Vienna Standard Mean Ocean Water (Craig, 1961).

3.4.7 Geochemical Interpretation

Geochemical interpretation of the analysed samples from field work was undertaken using a combination of box plots, piper diagrams and spatial maps. A box plot of major ions and water quality parameters was plotted to understand the spread of ion composition and to identify if any water quality parameters were out with acceptable limits. A piper diagram presenting results from boreholes, shallow wells, and river water was plotted to identify dominant ion compositions and geochemical evolution trends. Groundwater and shallow well samples were geospatially plotted in QGIS based on their major ion composition identified from the piper diagram interpretation in order to understand spatial distribution.

3.4.8 Isotopic Interpretation

Isotopic interpretation of the analysed samples from field work was undertaken using bivariate ratio plots of δ18O vs δD, δ18O vs altitude and D-excess vs δ18O that were plotted in Excel for borehole, shallow well and river samples. Samples were compared to both global and local meteoric water conditions by plotting a Global Meteoric Water Line (GMWL) defined as: $\delta D = 8\delta^{18}O + 10$ by Craig (1961) and a Local Meteoric Water Line (LMWL) that was created using data from a weather station in Mozambique, obtained from the GNIP database defined as: $\delta D = 7.7\delta^{18}O + 9.5$. This allowed for an interpretation of isotopic signatures, recharge location and type, the altitude effect, groundwater-surface water interaction, evaporation and vapour sources to be made.

4 A National Border Based Approach to Transboundary Aquifer Assessments at Relevant Scales: A Malawi Case Study[1]

4.1 Preface

This chapter is the first research chapter of the thesis. Available data and literature was gathered and critically assessed to identify current gaps in transboundary aquifer assessments within Malawi and the wider SADC. This chapter will set the scene for the rest of the thesis, identify research gaps within the field of study, and propose a way forward for research that this thesis will address.

This chapter answers RQ1 “How have transboundary aquifer assessments up until now allowed for transboundary aquifer management at the national scale?” It does so by first critically reviewing past transboundary assessments that have been focused at the regional level and on more obvious major aquifer systems. It also notes examples of individual transboundary aquifer system assessments. In doing so, multiple research gaps are identified (SO1). These include a lack of small scale transboundary aquifer assessments and the failure to recognise discontinuities within the hydrogeology of large aquifers. It is proposed that these could be addressed by systematically assessing all transboundary aquifers along countries international borders (SO2). The importance of these transboundary resources being managed within an IWRM scope and as part of hydraulically connected systems is then discussed highlighting current limitations to progression (SO3).

This chapter is a peer reviewed published paper[1] within a special Issue of the Journal of Hydrology: Regional Studies entitled ‘International Shared Aquifer Resources Assessment and Management’.

Paper reference:

[1]Fraser, C.M., Kalin, R.M., Rivett, M.O., Nkhata, M., Kanjaye, M. 2018. A national approach to systematic transboundary aquifer assessment and conceptualisation at

relevant scales: A Malawi case study. Journal of Hydrology: Regional Studies. Special Issue on International Shared Aquifer Resources Assessment and Management. Vol 20. Pages 35-48. https://doi.org/10.1016/j.ejrh.2018.04.001

Author contribution:

Conceptualization (C.M.F, R.M.K), data curation (C.M.F, R.M.K), formal analysis (C.M.F), investigation (C.M.F), methodology (C.M.F., M.O.R), validation (C.M.F., M.N., M.K.), visualization (C.M.F., M.O.R), project administration (R.M.K), supervision (R.M.K), writing original draft (C.M.F), review and editing (C.M.F., R.M.K., M.O.R., M.N., M.K.)

4.2 Abstract

Study Region: Malawi

Study Focus: Integrated water resource management of transboundary aquifers is becoming increasingly important. Without adequate and accurate scientific knowledge of the extent and characteristics, uninformed policy creation could lead to unsustainable management of these vital resources. This is particularly important within the Southern African Development Community where up to 85% of domestic water is supplied by groundwater. In this paper, Malawi is used as a case study to critically evaluate the current transboundary aquifer assessment frameworks within the region and their value in promoting IWRM. A series of illustrative conceptual models of TBA interactions pertinent to the Malawian national border are presented and we consider how TBA assessments may be integrated to national IWRM and strategic policy development.

New hydrological insights for the region: Current TBA assessments of Malawi and the wider SADC neglect multiple aspects needed for a national scale management plan. This includes full border TBA system identification alongside, given the geology of the region, consideration of the discontinuous nature of basement complex aquifers and localised alluvial deposits that both result in smaller scale aquifer units. Conceptualising such local scale complexity and encouraging countries to develop a strategy that systematically examines TBA systems along their national border at relevant scales will allow for more focused conjunctive policy creation and sustainable management of TBAs.

Key Words

Transboundary, Groundwater, Hydrogeology, Integrated Water Resources Management (IWRM), Africa, Malawi

4.3 Introduction

Groundwater has often been described as an invisible resource, yet it is important to recognise that almost 98% of the world's available freshwater resources is groundwater. Integrated water resources management acknowledges the important role of groundwater within frameworks that can sometimes be unduly surface water focused. The importance of IWRM is recognised in Sustainable Development Goal (SDG) 6 – 'to ensure availability and sustainable management of water and sanitation for all' (UN, 2017). Groundwater development is central to meeting SDG 6. A pressing need through IWRM is to recognise that many aquifers identified for resource use may cross national borders. It is then critical that transboundary cooperation comes into play to allow sustainable and equitable groundwater use by stakeholder nations involved.

Worldwide, water use is increasing due to growing water, sanitation and hygiene (WASH) demands. Africa is heavily reliant upon groundwater, including transboundary groundwater, with an estimated 75% of its population dependent on this resource for basic water supplies (Altchenko and Villholth, 2013). Investment in reliable water supplies will continue to depend on the development of groundwater resources. This may include the exploitation of transboundary aquifers (Giordano, 2009; MacDonald and Calow, 2009). This paper will focus primarily on Malawi, one of the 15 countries within the Southern African Development Community, a sub-continental region of Africa where widespread groundwater development is needed to address SDG 6. Effective groundwater management by some SADC member nations is faced by multiple challenges. These include little or no adherence to abstraction licensing legislation, low annual natural recharge in arid to semi-arid localities, low aquifer storage and vulnerability to climate change; all of which provide critical impetus to the development of a science-based strategy for groundwater management (Smith-Carrington and Chilton, 1983).

The term 'transboundary water' is used to describe a water body that crosses two or more international country borders. This can be in the form of rivers, lakes and groundwater (UN Water, 2014). An aquifer is a hydrostratographic unit that stores and transmits groundwater. An aquifer becomes transboundary when it crosses one or more international political border and thus has the potential for groundwater exchange between neighbouring countries (Wada and Heinrich, 2013). The challenge faced by countries is to reliably define aquifer connectivity and groundwater movement at their borders. Often this is with limited data available, or data not shared. This knowledge then needs to be translated to accessible conceptual models that can underpin science based policy implementation clearly and accurately.

We propose that in order to meet SDG 6, there is a need for countries to develop strategies that systematically identifies and screens TBA units along its national border. This will allow countries to characterise TBA connectivity and transmission of groundwater over their entire national border length. This includes conceptualising how abstraction on one side of a border may influence groundwater and surface water availability on the opposing side. Where influence is judged to be significant, this should trigger development of joint data collation efforts to underpin TBA policy and agreements. We further advocate that systematic TBA screening along a national border should not only examine “major aquifer” systems where connectivity is already known, but also include “minor” aquifer systems. Whilst not as geographically extensive, individual minor aquifer TBAs may be locally significance especially where relatively short distances separate neighbouring country communities. Furthermore, TBA connectivity of more major aquifer systems should not be assumed. Whilst extensive over tens of km scales or more, aquifers may still be locally discontinuous (e.g. due to structural faulting and weathering differences) and their local connectivity should be assessed.

Within the developing world context, technical data and financial resources are often limited. Here, desk-based screening using available data to conceptualise TBA connectivity is critical. Development of conceptual models of TBA interaction within a wider system, both generic and locally bespoke, is fundamental. Consideration of the TBA status of Malawi, a low-income developing country bordered by Mozambique, Tanzania and Zambia is made here as an example. A critical assessment of the current status of TBAs in Malawi is presented with the overarching goal to contribute to the development of a Malawian national approach to systems-based TBA assessment and conceptualisation at relevant local scales. The aims are to:

- Critically review Malawi's current status of TBA assessments that focus on more obvious major aquifer systems.

- Make a case for systematic TBA assessment along its national border length addressing minor, local aquifer systems and groundwater/surface water interactions.

- Develop conceptual models of TBA interactions relevant to its national border, but of generic value across the SADC.

- Consider how TBA assessments might be integrated to national implementation, strategic policy development and agreements with neighbouring countries.

4.4 Study Area

4.4.1 Malawi Study Setting

Africa is a continent challenged by limited water supply, poor quality of living, and economic uncertainty. Compared with Europe, cooperation over the management of Africa's transboundary rivers, lakes and TBA systems is significantly less developed (Scheumann and Alker, 2009). The SADC (Figure 4.1) was established in 2004 to bring together countries within the south-eastern African continent to improve living situations for large populations of people. Malawi, one of the 15 countries within the SADC, lies between 9°S and 17°S (latitude) and 33°E and 36°E (longitude). It extends across an area of 118,484 km^2 stretching 853 km N – S and 257 km E – W (Chavula, 2012). Lake Malawi covers 23.6% of the country, the third largest freshwater lake in Africa. Malawi's population is estimated to be 18.3 million (Worldometers, 2017) of which 90% live in rural areas. Its main economic income is generated from agriculture, with subsistence farming common amongst the rural population

(Government of Malawi, 2012). With less than 1,400 m^3/year/person of available total renewable water resources, Malawi is one of the most water-stressed countries in the world (Government of Malawi, 2012). This is largely due to the lack of infrastructure within the country to support large-scale management of water resources and much of its rural population accessing groundwater through hand-dug wells or low-capacity boreholes fitted with hand pumps.

Tens of thousands of water points now exist across Malawi (Pavelic et al., 2012); and added to daily under the SDG 6 agenda efforts. With the population of Malawi set to rise to 26.5 million by 2030 and renewable water resources likely to decline due to deforestation and climate change impact, Malawi could become water scarce with available total renewable water falling below 1000 m^3/year/person in the next 13 years. These valuable groundwater resources are vulnerable to pollution threats that may be poorly constrained (Back et al., 2018). Sparse monitoring of both groundwater quality and levels can also lead to a poor knowledge base for management (Rivett et al., 2018a). Such factors, and others, indirectly influence the strategic development of TBA assessment and management (Rivett et al., 2018b).

4.4.1.1 Regional Geology and Hydrogeology

The geology of the SADC is varied. It is composed of a combination of crystalline basin complex rock units interconnected with younger orogenic belts of metamorphic rocks and large sedimentary basins underlain by basement. The east of the region is heavily influenced by structural tectonics creating a complex geological history (Ramoeli, 2009). The East African Rift System (EARS) runs 2100 km from Uganda to Malawi and formed during the onset of the Miocene. It can be seen at the surface as aligned tectonic basins forming rift valleys separated by uplifted continental blocks (Chorowicz, 2005) that extend from Mozambique to Ethiopia. The rifts of the Western Branch of the EARS, where Malawi resides (Figure 4.2), are often filled with sediments or water (Specht and Rosendahl, 1989).

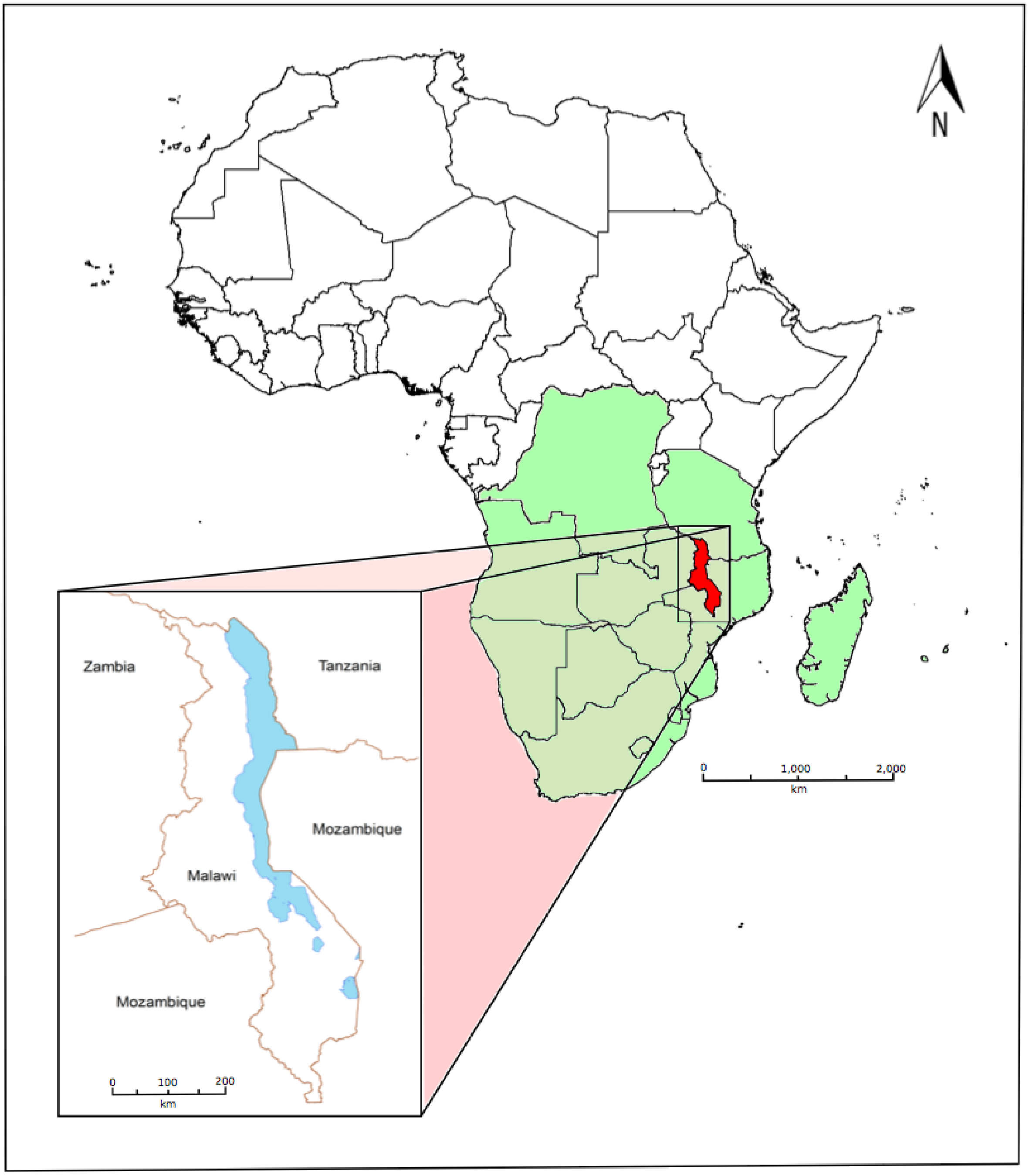


Figure 4.1 - Map of Malawi surrounded by Zambia, Mozambique and Tanzania illustrating Malawi's position (red) in relation to the African continent and the SADC (green)

4.4.1.2 Malawi Geology and Hydrogeology

The EARS large-scale rifting heavily influenced the topography and morphology of Malawi (Monjerezi and Ngongondo, 2012). This is through the creation of four main physiographic areas; the plateau, the uplands, the rift valley escarpment and rift valley plains. The plateau area represents the largest proportion of the topography of Malawi and is comprised of highly faulted basement gneiss (Smith-Carrington and Chilton, 1983).

The rift valley, where the Shire River Basin is located, forms the most significant structural feature of Malawi. It comprises a series of half-grabens that section into 60-100km long extensional basins formed by faulting offset from the EARS. This is bordered on one side by steep normal faults and by en-echelon step-faults with minor vertical offset on the other side of the valley (Ebinger et al., 1987; Ring and Betzler, 1995) (Figure 4.2). These rift events have played a significant role in the distribution of the aquifer lithologies within Malawi and the SADC (Smith-Carrington and Chilton, 1983).

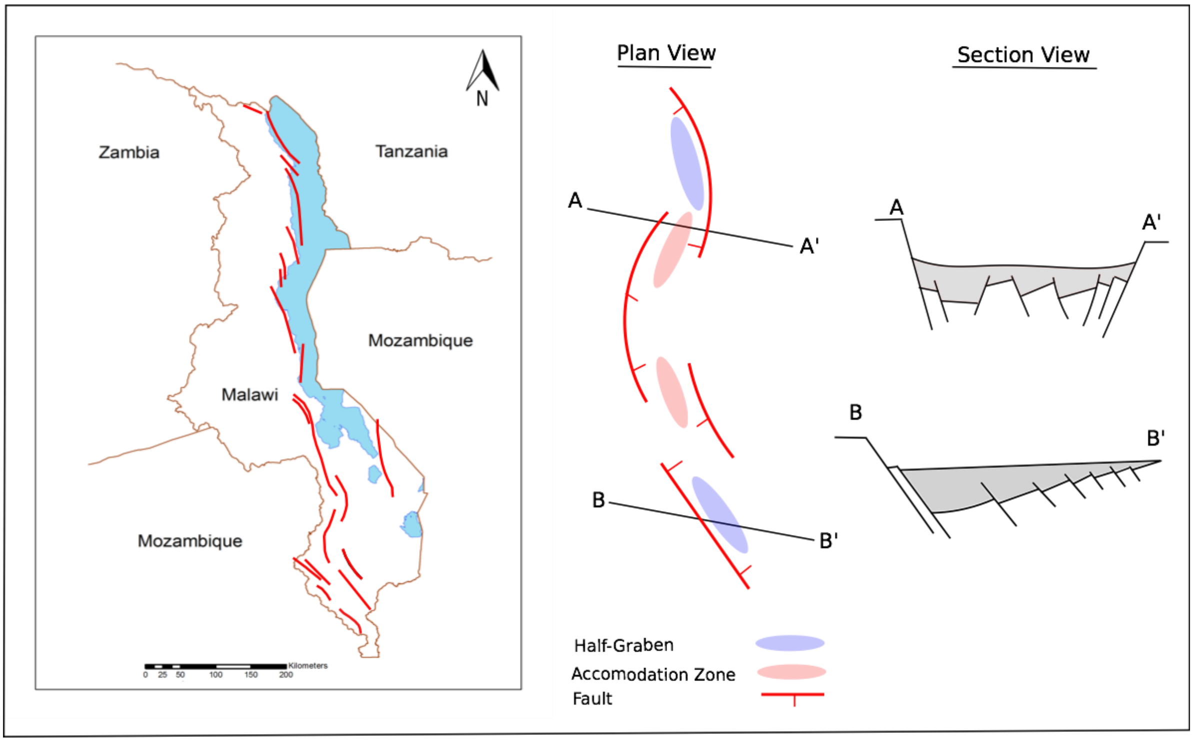


Figure 4.2 - Malawi's Rift faults and basin structure (left) with a plan and cross section view through the southern region (right). Modified from (Delvaux, 1991)

Differing lithologies in Malawi provide varying productive water-bearing units theoretically allowing a large proportion of Malawi access to groundwater. Accurate knowledge of the geology and hydrogeology is important to determine the aquifers that may be transboundary. The main water bearing geological units in Malawi are summarised below in order of increasing importance (Bradford, 1973):

(1) Precambrian to Lower Palaeozoic weathered and (2) fractured basement rocks; composed of metamorphic rocks of varying lithology but primarily gneiss and granulites. These are Malawi’s most abundant geological units and account for 96% of the total land cover. These are low storage and low transmissivity aquifers with borehole yields between 0.5 and 0.8l/s (Government of Malawi, 2006. Upton et al., 2016).

(3) Permian to Triassic Karoo sedimentary rocks; units exhibit low porosity and intergranular permeability due to calcite cementation. Groundwater flows through fractures and thus aquifers have low to moderate productivity; although this may be increased in the south of Malawi where more heavily faulted (Smith-Carington and Chilton, 1983; Upton, 2016).

(4) Cretaceous sedimentary rocks; outcrops tend to be limited and of infrequent occurrence across Malawi. The units tend to exhibit good storage and high permeability, and tend to be highly fractured. There are extensive deposits across the southern extent of the SADC that are significant sources of water (Government of Malawi, 2006; Upton et al., 2016).

(5) Lower Jurassic weathered Karoo basalts; outcrops are limited to small regions within Malawi. These can form a valuable localised resource due to spaces at contacts between lava flows and vesicular cavities providing a flow path for water alongside jointing and faulting of the lava. Permeability within the units is hence high which provides a high quality and low mineralised water source (Smith-Carrington and Chilton, 1983).

(6) Quaternary unconsolidated alluvial deposits; found across the flood plains of rivers. These form Malawi’s most productive aquifers. They are spatially variable across the country with highest quality water being available within gravel beds where permeability is high (Smith-Carrington and Chilton, 1983).

Malawi's groundwater resources are representative of the east of the SADC and parts of the south of the SADC where the basement complex is exposed. Similarities can also be seen throughout the world where large proportions of the groundwater come from basement rocks that tend to support only low yielding boreholes and provide only local water supplies. Parallel cases of large scale basement complex aquifers can be seen in South Asia, South America and Australia (Wright and Burgess, 1992).

4.5 Review of Malawi's Current Status of TBA Identification

4.5.1 Regional Context

The main driving force for international TBA assessments is the UNESCO-IHP (United Nations Educational, Scientific and Cultural Organization - International Hydrological Programme) through the Internationally Shared Aquifer Resources Management (ISARM) initiative and the International Groundwater Resources Assessment Centre (IGRAC). IGRAC publishes a 'Transboundary Aquifers of the World' map with all known TBAs displayed based on the most recent inventory results from many projects globally. This compilation of all international data constitutes a valuable starting-point for governments. There are 592 TBAs currently identified worldwide. 80 of these are located within Africa (Figure 4.3) (IGRAC and UNESCO, 2015a; IGRAC and UNESCO, 2015b) accounting for 43% of the continental land surface (Altchenko and Villholth, 2013). A large proportion of TBAs within Africa were identified through the 'Global Environment Facility Transboundary Waters Assessment Program' (GEF-TWAP) regional assessments (ILEC et al., 2016). The aim of the GEF-TWAP was to provide the first global scale assessment of all transboundary waters. GEF-TWAP regional assessments were carried out by an appropriate representative from each country and then collected and streamlined by the project.

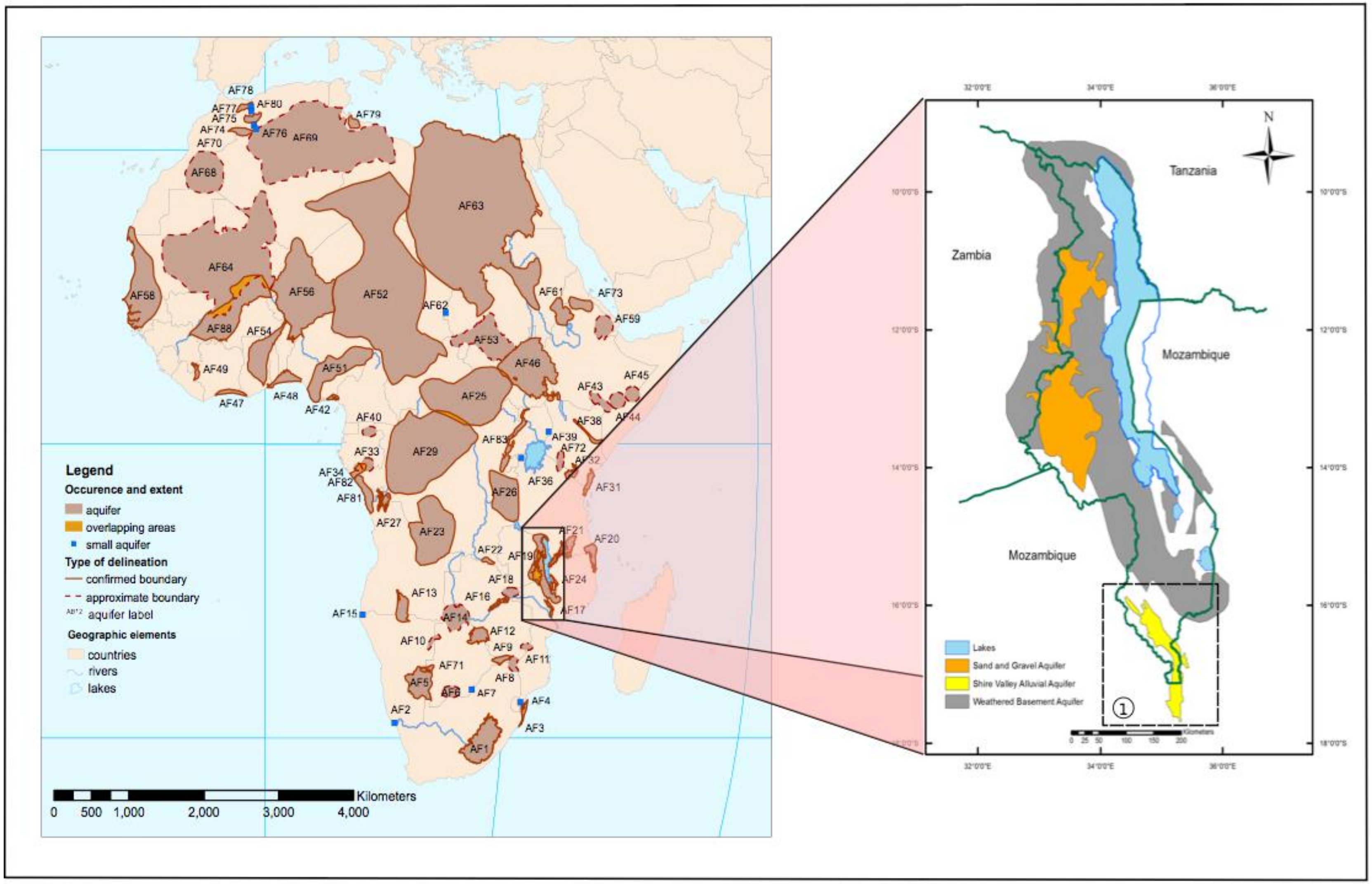


Figure 4.3 - Map of the African continent illustrating the current known transboundary aquifers highlighting current identified transboundary aquifers of Malawi shared with surrounding countries (modified from IGRAC and UNESCO, 2015b). See figure 4.5 for a reinterpretation of the south of Malawi transboundary aquifers, area illustrated in point 1

Table 4.1 - Summary of current identified TBAs within Malawi (ILEC et al., 2016; Upton et al., 2016; Davies et al., 2013). For aquifers extent and location see Figure 4.3

Aquifer Name	Lithology	Transmissivity (m^2/day)	Total area extent (Km^2)	Aquifer Thickness (m)	Aquifer Productivity	Aquifer Type	Confinement	Involved Countries
Weathered Basement	Crystalline-metamorphic basement rocks	<5-6	110,000	30-45	Low to moderate	Mainly single-layered, multi-layered in north	Semi-confined to confined	Malawi Tanzania Zambia Mozambique
Sand and Gravel	Colluvium overlying weathered metamorphic basement gneiss	<5-26	23,000	20-60	Low to moderate	Single-layered system	Unconfined to semi-unconfined	Malawi Zambia Mozambique
Shire Valley Alluvial	Tertiary/Quaternary sediments	50-300	6223	30-150	High to very high	Single-layered system	Unconfined to semi-unconfined	Malawi Mozambique

4.5.2 Malawi Context

The GEF-TWAP and the most recent 'Transboundary Aquifers of the World' identify three TBAs shared between Malawi and its bordering neighbours (Table 4.1; Figure 4.3) (ILEC et al., 2016; IGRAC and UNESCO, 2015a; IGRAC and UNESCO, 2015b). Malawi and its surrounding neighbours possess geological and hydrogeological maps (Geological Survey of Malawi, 1970; Government of Malawi, 1987). These data were used via the GEF-TWAP in 2014 (ILEC et al., 2016) to assist in the reinterpretation of the extent of a TBA previously identified as crossing the Malawi-Tanzania and Malawi-Zambia border. Further information was also collected on two other identified TBAs shared between Malawi and Zambia, and Malawi and Mozambique.

4.5.3 TBA Assessment Gaps

A number of gaps have been identified that must be addressed in order for Malawi to manage their aquifers on a local scale, as well as nationally. Firstly, the Shire Valley Alluvial Aquifer (Table 4.1) is not the only potential alluvial transboundary unit within Malawi. Other small scale unconsolidated alluvial deposits can be found across the flood plains of other rivers throughout the country, some of which are likely to be transboundary. These have not been recognised on a regional scale most likely due to their limited extent and thickness. Although these smaller 'minor' aquifers may not contribute large quantities of water to Malawi and its neighbours, small communities situated relatively close to the national border may rely exclusively upon them for local drinking water, irrigation and other agricultural supply use. The identification of small scale aquifers is also important in countries like Malawi as they may provide baseflow to hydraulically connected river systems (Kingdon et al., 1999).

Karoo sedimentary units and basalts also outcrop in Malawi. Most of these units lie on the south west border of Malawi and are transboundary with Mozambique. In many other parts of the Southern African region, the Karoo Super Group has been seen to yield excellent quality and quantities of groundwater (Woodford & Chevallier, 2002; Cheney et al., 2006). This is potentially another TBA shared between Malawi and Mozambique that could be a valuable groundwater resource locally.

Within the TWAP regional assessment, the complexity of the basement complex that underlies the sand and gravel TBA (Table 4.1) is not considered (ILEC et al., 2016). It is composed of multiple complex, non-uniform lithologies that are important when considering water storage and flow, particularly close to the border. These different lithological units are discontinuous and subject to fracturing by faults; groundwater units of limited size are formed along these fracture zones, which vary locally in their yield potential depending on lithology (Wright and Burgess, 1992). Fractured basement aquifers often exhibit low transmissivity values and thus cross border groundwater flow may not be that significant. Still, the extent of local flow regimes should be considered and in particular the potential for cross-border flow and influence of abstraction from one border side upon the opposing side. Where local flow systems are more restrictive than previously thought, limited groundwater present may be supplying larger populations than it can realistically support. Local assessments at national borders of the hydrogeological unit are hence needed to ensure that communities, either side of a border, sustainably and equitably use the local groundwater available.

Storage within the basement complex is dependent on secondary porosity, available due to weathering and fracturing which is also spatially variable (Upton et al., 2016). Weathering usually declines with depth and therefore higher yielding units occur nearer the surface (Smith-Carrington and Chilton, 1983). Fracturing, however, forms along fault zones primarily within the rift valley of the southern limbs of the extensive EARS. Given the local differences between the degree of weathering and fracturing within the basement complex lithologies, these units cannot be considered as a single aquifer system and instead must be recognised to constitute multiple smaller systems dependent on the local conditions where local fracturing or weathering is significant enough so that groundwater can be stored. There are therefore large 'non-aquifer' areas of the basement complex not capable of groundwater storage, and other small local areas with intensive fractures or significant weathering providing sufficient yields (Upton et al., 2016). These aquifers are hence more discontinuous in nature than the alluvial or sand and gravel systems making them less of a transboundary issue in some places. Again, these factors point to the need for more local driven assessments of TBA systems at national borders.

4.5.4 Legal Provisions

Though transboundary surface water governance is regularly practiced nowadays, transboundary groundwater governance has received comparatively little attention to date (Eckstein, 2015). Globally, only six TBAs have a governing agreement in place compared to over 3,600 treaties relating to the use of transboundary surface waters (UNEP, 2002; cited by Eckstein and Sindico, 2014). This deficiency has prompted our work under the Climate Justice Fund - Water Futures Programme to support a country-wide evaluation of all groundwater resources within Malawi including TBA potential (Scottish Government, 2017). There are currently no legally binding agreements between Malawi and its neighbouring countries relating to the management of shared groundwater resources. There is, however, some cooperation between Malawi and Mozambique concerning the management of the Shire River Basin. In 2003 a treaty was signed by both parties on 'The agreement on the establishment of a Joint Water Commission' to improve responses to flooding in the basin (IWMI, 2015). A World Bank-funded project focused on the Shire River Basin is also on-going, but is primarily focused on the Malawi side of the border. It does not assess potential TBA issues (The World Bank, 2010).

There are multiple protocols and policy instruments within the SADC that include groundwater and transboundary management within their scope. These include the Regional Water Policy adopted in 2005, the Regional Water Strategy adopted in 2006 and the Regional Strategic Action Plan on Integrated Water Resources and Development Management. The most relevant to TBA management is the Revised Protocol on Shared Watercourses (SADC, 2000). This protocol recognises that many watercourses within the SADC are shared among several member states. It aims to foster closer cooperation amongst these states for the protection, management and use of these shared watercourses within the region (e.g. Article 2(a); Article 3, 8(a)).

Member states agree to cooperate on projects and exchange information on shared watercourses, consulting with each other and collaborating on initiatives. Within Malawi's own Water Resource Act (2013), a provision states that Malawi must consider its "obligations relating to shared waters" (Part 4, Section 41 (e) (ii)) when granting an abstraction licence and issuing a permit to discharge effluent into a watercourse. Clarity is required in the forthcoming policy on how this provision binds Malawi to uphold the SADC Revised Protocol on Shared Watercourses (2000) and customary international water law principles such as no significant harm, or whether the provision is just a placeholder for any future obligation regarding shared waters that Malawi might legally accept to be binding on it.

Within international water law, the UN Draft Articles on the Law of Transboundary Aquifers, 2008 (ILC, 2008) and the Convention on the Law of the Non-Navigational Uses of International Watercourses 1997 (UNWC, 2014) are two instruments available to countries looking to foster agreement over the management of their transboundary resources. The Watercourses Convention is limited by its narrow and restricted definition of a 'watercourse' which suggests that not all types of aquifers come under the regulations of the Watercourse Convention, including fossil groundwater (Martin-Nagle, 2016). Furthermore, the Watercourse Convention does not have a standard definition of what constitutes a TBA alongside suggested criteria for the management of these resources.

The UN Draft Articles on the Law of Transboundary Aquifers in contrast facilitate an international legal framework that focuses on all shared groundwater resources and conjunctive management of both groundwater and surface waters (Sanchez et al., 2016). It does this by including both natural recharging and non-recharging (i.e. fossil) TBAs within its scope and recognising that TBAs can be hydraulically linked to surface waters. However, they do have limitations of their own, particularly within the exact definition of an 'aquifer' and the exclusion of 'recharging-only' states (i.e. those states from which recharge comes from but who hold not proportion of the aquifer within its border) from the scope (Eckstein 2007). As Draft Articles, they can only provide direction or guidance for countries who choose to use them and consequently hold no legal obligations. If localised and regional TBA management is to be supported by international law, adopted instruments will need to recognise the complexity of the hydrogeological systems governed.

4.6 Discussion

4.6.1 A case for systematic national border-based assessments

Many countries are now recognising the importance of TBA identification as a contribution to IWRM. They are assessing key TBAs, most often identified through regional initiatives such as the GEF-TWAP as previously described. This includes Western Europe, Kazakhstan, Russia and the United States of America (European Commission, 2015; Puri & Aureli, 2005; Zektser, 2010). Sanchez et al. (2016) describe known TBAs along the Mexico-USA border with a significant collation of available hydrogeological data. The aquifer systems are laterally extensive and this mode of assessment may fail to resolve the potentially more local transboundary issues where more local minor aquifer assessments become more valid. This need for greater resolution is alluded to by Rivera (2015) who reviews the ten main identified TBA systems along the Canada-USA border, but acknowledges that more TBAs likely remain to be resolved.

Individual TBA system assessments are more common, for example, the detailed assessment of the Milk River Formation between Canada and the United States (Petre et al., 2016; Petre et al., 2015). The study establishes a geological and hydrogeological conceptual model of the TBA system characterising flow directions, recharge zones and abstraction rates. The conceptualisation underpins the development of effective strategies to sustainably manage the resource. Such dedicated aquifer system-focused assessments, whilst critical, do not represent the whole transboundary circumstances of a country. Such detailed assessments also require extensive data and financial resources that may not be available to many developing countries.

Our premise is that there is a need for countries to develop a TBA assessment strategy that systematically screens its entire national border at relevant scales. For some countries, this may include local scales where more minor aquifers may form important resources that are relied upon by rural communities. Overall abstraction volumes may not be that large, but still could be significant locally, especially in SADC arid-semi-arid environments where recharge may be low. This drives the need for relatively local TBA assessment, albeit within the context of the wider geological/hydrogeological systems. A flow diagram is developed in Figure 4.4 to illustrate the fit of such a national border-based TBA assessment within an overall TBA assessment framework.

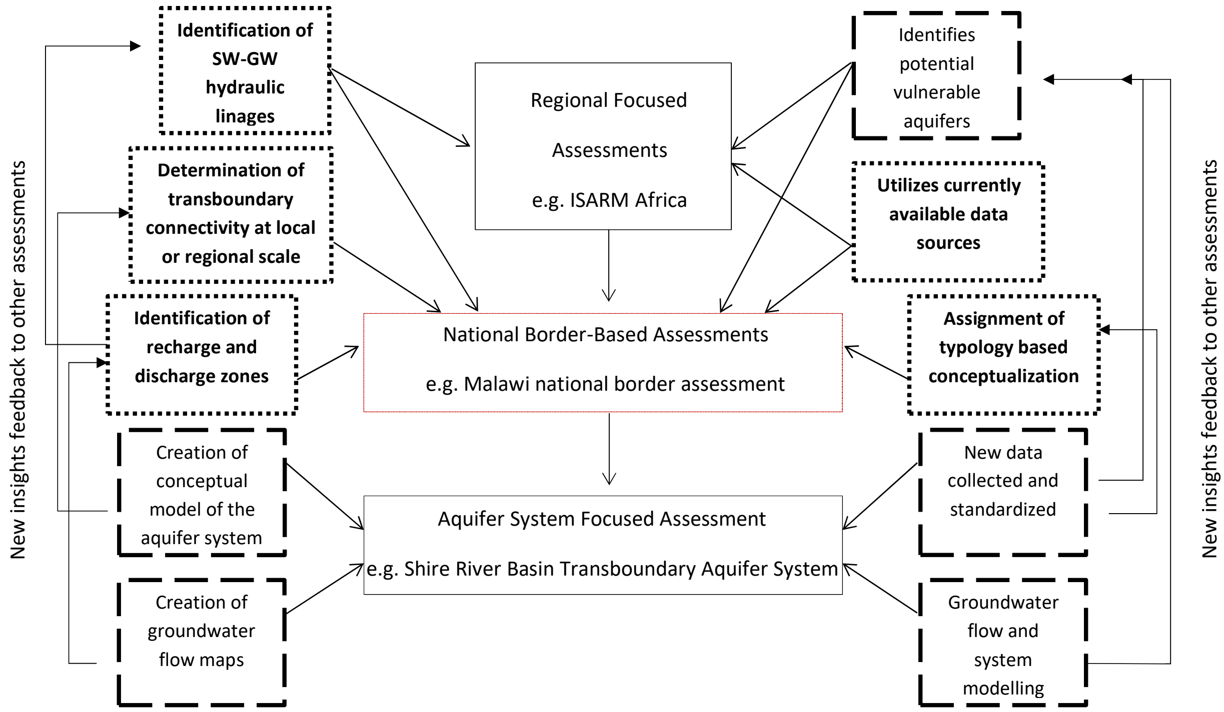


Figure 4.4 - Flow diagram illustrating the place for national based boundary assessment within an overall framework. Gathered information from regional assessments can feed in to inform the national border based assessments. These can then be used to identify key aquifers that require a more detailed system-focused assessment. New data and insights can feed back to other assessments in a looped system

The transboundary connectivity of more major aquifer systems should not be assumed and requires consideration within the strategic approach (Figure 4.4). Their potential locally discontinuous nature due to faulting and lithology variation (heterogeneity) needs to be understood. Detailed hydraulic functioning at local scales in the vicinity of national borders should be assessed with particular emphasis on assessing evidence for barriers to groundwater flow. This may be aided by improved recording, archiving and computer access to geological log, water level and geophysical monitoring data than is often not practiced in the developing world.

For both minor and major aquifer systems, the potential complicating influence of surface water flows hydraulically connected to these aquifer systems also needs to be explicitly recognised at relevant scales (Figure 4.4). Groundwater – surface water interactions may result in groundwater flow to surface water and vice versa. These may alter seasonally and groundwater abstraction variation. Conditions may likewise vary upstream and downstream of a country border.

The aim of national border based assessments will be to allow for identification of a country's groundwater resources that are most vulnerable to TBA influence and cross-border flows. Whilst a desk-based study may frequently lack data and resources to make a complete assessment, it should enable some prioritisation and selection of higher risk TBA scenarios that warrant further analysis and targeted (field) data collection (Figure 4.4). Contributing metrics to evaluating the at-risk status may include not only TBA hydraulic connectivity, but also consideration of near-border population levels and relative water abstraction rates either side of a border. Such an approach helps to address SDG 6 - Target 6.5 requiring IWRM with transboundary cooperation where necessary (UN Water, 2015).

Our on-going TBA assessment work in Malawi seeks to account for the expected discontinuous nature of the basement complex arising from lithologies, and will consider the differences between the weathered and fractured zones within the basement complex to evaluate the significance of transboundary groundwater exchange. The first results of the reinterpretation of the hydro-stratigraphic units shared with Mozambique in the southern extent of Malawi (Figure 4.5) illustrate the complexity that can be lost in a regional scale assessment. Whereas the TWAP (ILEC et al., 2016) Southern and Eastern Africa sub-region recognises only one TBA system, the Shire Valley Alluvial Aquifer, in reality exists a multilayer sedimentary aquifer and a discontinuous basement complex system that dominates a large proportion of the border.

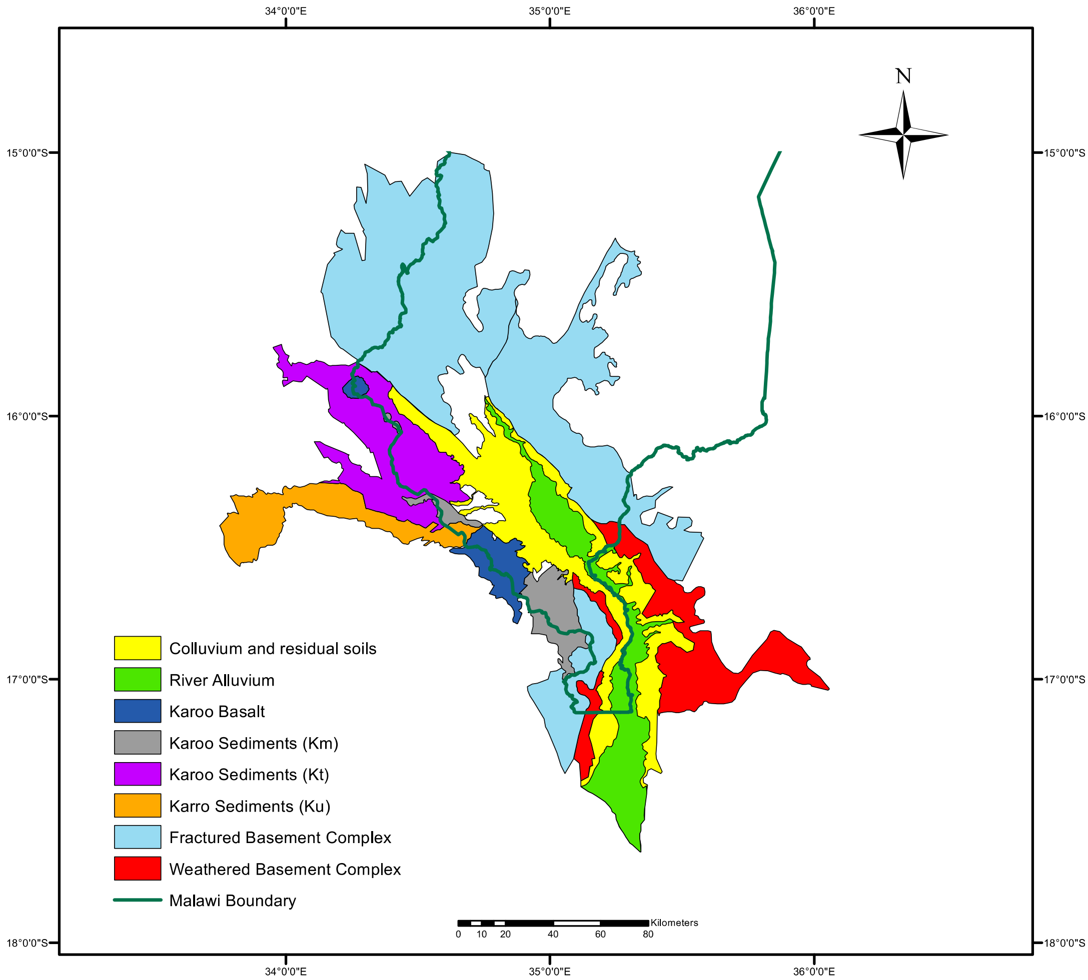


Figure 4.5 - A reinterpretation of the transboundary aquifer units of Southern Malawi shared with Mozambique. For reference of location see point 1 on figure 4.3

4.6.2 Conceptual models for TBA interactions

A series of illustrative conceptual models of TBA interactions applicable to the Malawian national border are developed below. They are anticipated to be of generic value elsewhere, particularly across the SADC. These models assume low thickness alluvial or basement complex aquifers with low to moderate transmissivity/hydraulic conductivity at or near the border.

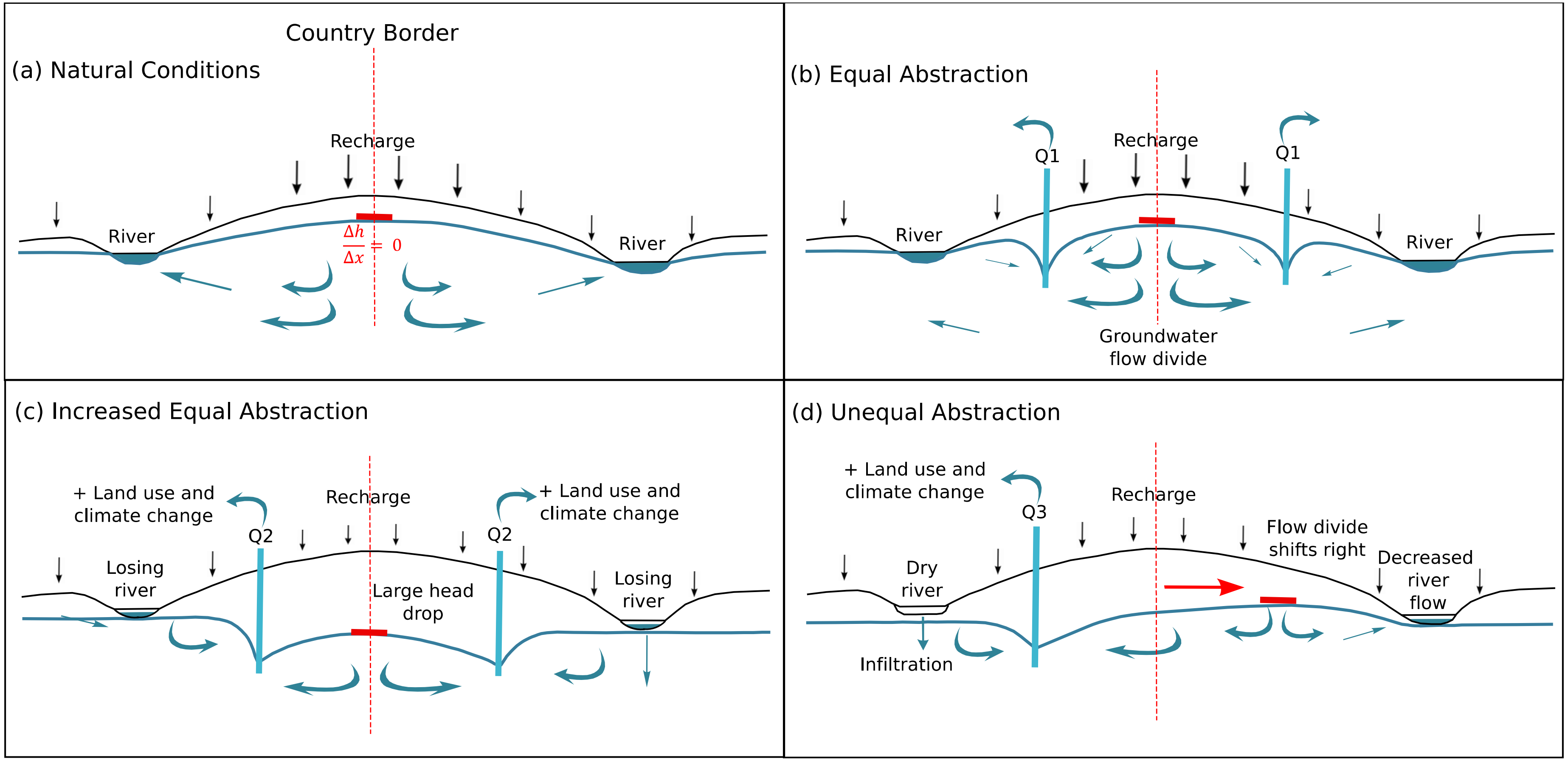


Figure 4.6 - Equal and unequal abstraction from an equally shared transboundary aquifer between two states and sustainability implications

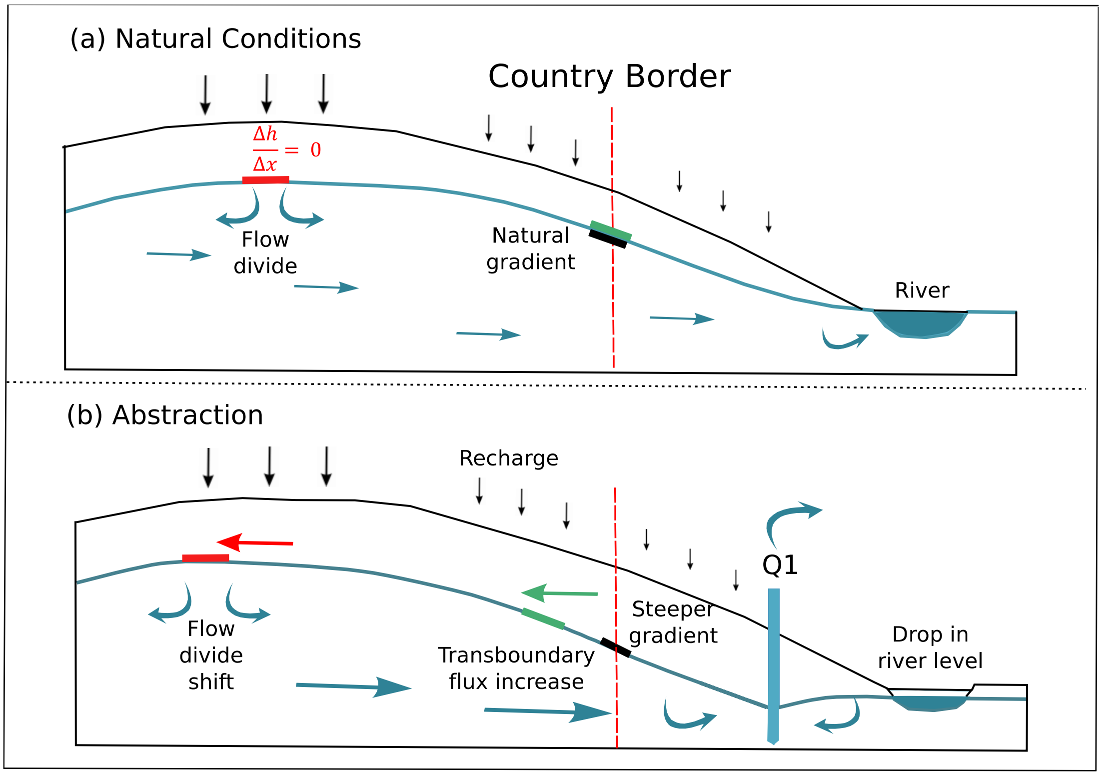


Figure 4.7 - Sustainable and non-sustainable transboundary abstraction within an unequally shared transboundary aquifer system

Figure 4.6 portrays an idealised low thickness, symmetric transboundary aquifer (i.e. the national border lies in the middle of the aquifer). Figure 4.6(a) illustrates the aquifers natural conditions and Figure 4.6(b) shows the addition of a sustainable abstractions either side of the border. The flow divide remains central with the resource equally shared. Increased groundwater abstraction may still result in an equal resource share either side of the border but a non-sustainable use (and ultimately a loss) of groundwater and negative impacts on surface water (losing rivers) on both sides of the border (figure 4.6(c)). Figure 4.6(d) illustrates unequal abstraction which shifts the groundwater flow divide resulting in the share of groundwater becoming unequal and considerable surface water impact due to a drop in the water table. The final scenario is particularly pertinent to Malawi where local villages close to the border are heavily reliant on groundwater supplied from thin but abundant alluvial aquifers, some of which are transboundary. Equally, the reverse is also possible if a neighbouring state has a higher abstraction rate.

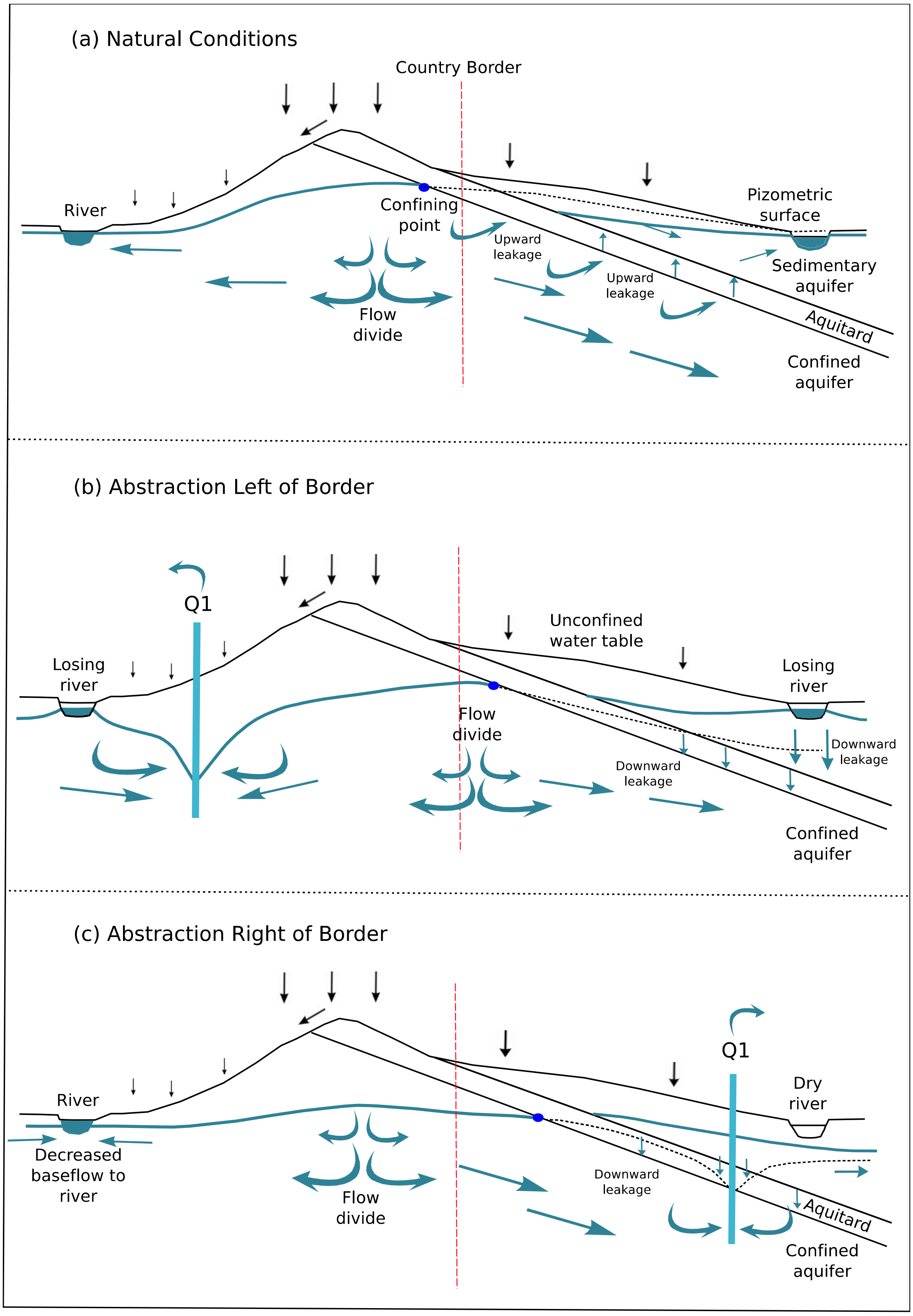


Figure 4.8 - The implications of abstraction from a confined transboundary aquifer system

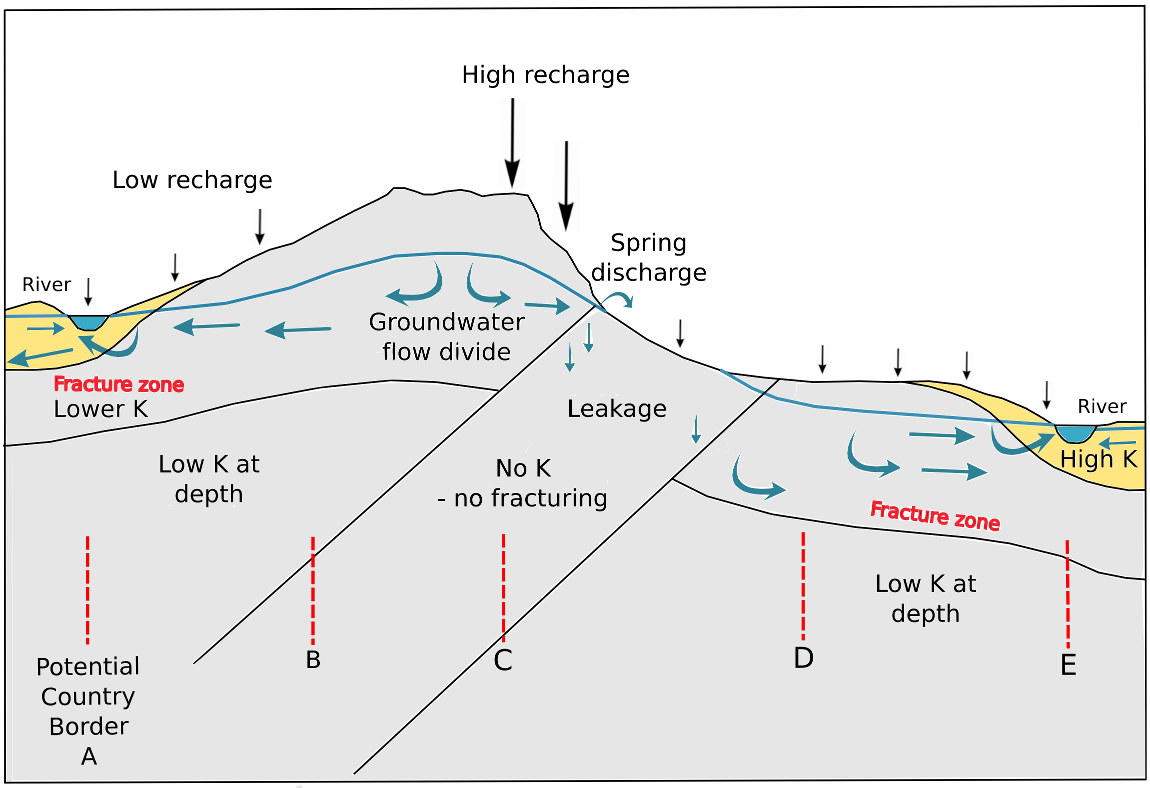


Figure 4.9 - Discontinuous fractured rock aquifer and boundary implications for transboundary groundwater flow

Figure 4.7 conceptualises a low thickness alluvial aquifer with the country border in an asymmetric position; a better representation of reality. The recharge across the border is not equal and a larger proportion of the aquifer resides within one country. Abstraction (b) on one side of the border complicates the situation by shifting the flow divide away from the border and this impacts surface water within the abstracting state. Importantly, the abstraction also increases the speed at which the groundwater is moving across the border, as a steeper gradient across the border causes an increase in transboundary flow. Climate change or deforestation within the scenario could also reduce recharge significantly within the system, as is the case for Figures 4.6, 4.8 and 4.9.

Figure 4.8 conceptualises a semi-confined system where the TBA is not receiving natural recharge on one side of the border due to an overlying low permeability aquitard. Recharge to the confined aquifer occurs to one side of the border. During natural conditions (Figure 4.8(a)) the confined section of the aquifer on the other side of the border is under artesian pressure resulting in upward leakage through the aquitard and into the aquifer above. This leakage hence provides some support to river flow to the right of the border contributing to baseflow. Adding an abstraction on either side of the border could cause leakage to be reversed resulting in a losing river scenario (Figures 4.8(b) and 4.8(c)). Increased abstraction may result in complete loss of baseflow to the river. Such cases are illustrative of TBA connectivity on the management of both surface and groundwater resources.

The final conceptual model (Figure 4.9) is of basement complex, with an overlying discontinuous alluvial aquifer; a common scenario across the SADC. Assuming a natural flow regime, there are a variety of transboundary implications based on where the border sits (Borders A-E). Borders A and E for example result in transboundary groundwater flow through both unconsolidated alluvial sediments and fractured basement rock. Borders B and D would exhibit just fractured rock groundwater flow, and border C, close to the groundwater flow divide, would have fairly limited groundwater contributions from the opposing border side contributing to aquitard leakage and the shown spring discharge. This conceptualization highlights how variable aquifer lithologies and discontinuities throughout the basement complex can cause different transboundary system types that need to be considered on an individual and local basis. Figure 4.9 could have been developed to portray a different basement complex lithology or a weathered zone instead of a no fracture zone; this again could result in the unit being broken up into smaller aquifer units.

4.6.3 Integrated Water Resource Management

Although widely recognised that groundwater is an integral part of many hydrological systems, many IWRM schemes still omit transboundary groundwater from their scope. Whilst some groundwater resources may appear to have weak hydraulic connectivity to other system compartments or contain fossil groundwater (Martin-Nagle, 2011), many systems do display significant connectivity between groundwater and surface water systems (Rivera, 2015). It is critical to recognise this connectivity within any TBA assessment and IWRM framework adopted.

‘Water Resource Units’ (WRUs) have long been defined in Malawi that sub-divide the country into 17 separate physiographic regions and 66 sub-region units based upon surface water catchments (Smith-Carrington and Chilton 1983). More holistic IWRM at a national level needs to recognise that many aquifers cross these units and thereby allow water transfer between them. This may result in IWRM tensions as neighbouring unit officials could manage their connected groundwater resources differently. This scenario may be further complicated where transboundary issues also arise. IWRM of TBAs requires consideration of not only recharge sources and abstraction areas, but also surface water (recharge/discharge) connectivity to these aquifer systems. Future water resource policy in Malawi will need to increasingly recognise that linkage of physiographic regions and groundwater (including transboundary groundwater) is required to achieve IWRM and SDG 6. It is not unreasonably surmised that similar challenges (with local variation) to those faced by Malawi are likewise faced by other countries.

Various foundations for IWRM and hence TBA management beyond Malawian borders are provided for by surface water catchment based initiatives. Within Africa, ‘River Basin Organizations’ (RBOs) have been developed to foster joint water cooperation between stakeholder countries built upon the African Water Vision 2025 (UN Economic Commission for Africa, 2001). Malawi is part of the Zambezi Watercourse Commission (ZAMCOM), one of six River Basin Organizations within the SADC region. Similar to the Malawian WRUs, these are surface water catchment management based, often without mandate to manage transboundary groundwater or coordinate its management between the stakeholder basin states. Where mandates do exist (e.g., Orange-Senqu River Commission), technical skill or financial resource limitations inhibit the progress of groundwater management. Consequently, the groundwater aspect of the river basin is often managed indirectly to the rest of the hydraulic system or not at all.

Fostering institutes that cooperate conjunctively on hydraulically linked surface and groundwater management on both the local, national and international scale is advocated to move forward with IWRM within the SADC. Recent progressive effort to account for groundwater management within SADC member states is evident through establishment of the SADC Groundwater Management Institute (SADC-GMI) hosted by the Institute for Groundwater Studies in Bloemfontein, South Africa. Their aim is to support the sustainable management of groundwater at national and transboundary levels across SADC member states (SADC-GMI, 2016). Our national border-based TBA assessment approach is seen to support this initiative.

4.7 Conclusion and Recommendations

Integrated water resource management of transboundary groundwater is becoming increasingly important and can vitally underpin international achievement of SDG 6. This paper has critically assessed previously identified TBAs in Malawi and introduced the need for Malawi and other countries to more generally develop a TBA strategy that systematically examines its entire national border at relevant scales in order to establish and prioritise TBA connectivity. It is fundamentally built around conceptual models of TBA connectivity and interaction that are presented here and offer generic value elsewhere.

Within the African developing world context personified by Malawi, an entire national border approach may initially require local-scale desk-based assessments driven by the presence of rural low-density populations, dispersed community water points, frequent minor aquifer systems and the potential for disconnected aquifer units (e.g., by faulting or weathering). Whilst aquifers are often minor, they are nonetheless critically important to life and livelihoods in most cases. Our proposed approach outlined, and on-going in terms of detailed assessments throughout the Malawian national border length, is necessarily desk-based due to resource constraints in the developing world. It is nonetheless expected to vitally steer where future TBA efforts may be targeted.

Our border based TBA assessment approach is vitally overarched by an IWRM framework that recognises the connectivity of groundwater and surface water as a single hydraulic system. Such an approach is critical to informing and developing appropriate national management policies, international cooperation, and the development and implementation of science-informed TBA agreements that are workable. International law and policy guidance will need to recognise the complexity of hydrogeological-hydrological systems. Although the Draft Articles as indicated are moving in the right direction, limitations must be addressed in order to facilitate a framework that promotes IWRM of TBA systems. It is anticipated that such recognitions and approaches will pave the way for appropriate local/regional scaled sustainable and equitable management of the TBAs identified and safeguard water resources for all stakeholder nations involved.

4.8 Postface

This chapter answered RQ1 "How have transboundary aquifer assessments up until now allowed for transboundary aquifer management at the national scale?" It did so by first critically reviewing past transboundary assessments that have been focused at the regional level and on more obvious major aquifer systems. It also highlighted some examples of individual system transboundary assessments. In doing so, multiple research gaps were identified (SO1). These included a lack of small scale transboundary aquifer assessments and the failure to recognise discontinuities within the hydrogeology of large aquifers. It was proposed that these could be addressed by systematically assessing all transboundary aquifers along countries international borders (SO2). The importance of these transboundary resources being managed within an IWRM scope and as part of hydraulically connected systems was also discussed highlighting current limitations to progress (SO3).

On reflection, section 4.5.4 of this chapter could have also presented the UNECE Water Convention as a third international legislative option to Malawi for fostering transboundary aquifer agreements. At the time of the writing and publication of this paper (2016-2018), the focus of the Water Convention as an option for other non-European countries was only 1-2 years hence and it did not have the prominence it is gaining now in 2020. Thus, it was not considered at this time. Although Malawi is not a Party to the convention, other countries in Africa are starting to choose to. Chad and Senegal were the first African Parties to join in 2018 and, most recently, Ghana also acceded the convention alongside the Watercourses Convention (UNECE, 2020b).

The next chapter will now further explore the Malawi case study and shift focus to examine the transboundary nature of its aquifers more closely. It will present a methodology for a border based transboundary aquifer assessments and apply it to the Malawi case study. This next chapter will also discuss the current limitations of transboundary aquifer assessments and management that should be addressed to achieve SDG 6.5.

5 A National Border Based Assessment of Malawi's Transboundary Aquifer Units: Towards Achieving Sustainable Development Goal 6.5.2[2]

5.1 Preface

Chapter 4 identified gaps in current transboundary assessment approaches and made a case for border-based transboundary aquifer assessments at the national scale using Malawi as a case study. It did so by first critically reviewing past transboundary assessments that have been focused at the regional level and on more obvious major aquifer systems. It also highlighted some examples of individual system transboundary assessments. It was proposed that these could be addressed by systematically assessing all transboundary aquifers along countries international borders. The importance of these transboundary resources being managed within an IWRM scope and as part of hydraulically connected systems was also discussed highlighting current limitations to progress.

This chapter will now answer RQ2 - Are there more transboundary aquifers than previously thought in Malawi? In doing so, a methodology for a border based transboundary aquifer assessments is presented and applied it to the Malawi case study (SO4). In total, 38 transboundary aquifers are identified, a dramatic increase from the previous 3 identified. Descriptions of the transboundary aquifers within Malawi are then presented (SO5) and a discussion of the current limitations of transboundary aquifer assessments and management that should be addressed to achieve SDG 6.5.2 is given (SO6). These include institutional mechanisms, limited cross-border data sharing, limited groundwater monitoring, and a need to revisit the wording of the transboundary-focused SDG target and its indicators.

This chapter is also a peer reviewed published paper[2] in Journal of Hydrology: Regional Studies

Paper reference:

[2]Fraser, C.M., Kalin, R.M., Kanjaye, M., Uka, Z. 2020. A National Border-Based Assessment of Malawi's Transboundary Aquifer Units: Towards Achieving Sustainable Development Goal 6.5.2. Journal of Hydrology: Regional Studies. https://doi.org/10.1016/j.ejrh.2020.100726

Author contribution:

Conceptualization (C.M.F, R.M.K), data curation (C.M.F, R.M.K), formal analysis (C.M.F), investigation (C.M.F), methodology (C.M.F.), validation (C.M.F., M.K., Z.U.), visualization (C.M.F.), project administration (R.M.K), supervision (R.M.K), writing original draft (C.M.F), review and editing (C.M.F., R.M.K.., M.K., Z.U.)

5.2 Abstract

Study Region: Malawi

Study Focus: The adoption of the United Nations Sustainable Development Goal 6 in 2016 has triggered countries across the globe to assess and improve management and use of water resources. Monitoring of these resources is becoming increasingly important, and the management of transboundary water resources, in particular groundwater aquifers, required to meet SDG target 6.5.2, is lagging behind. It is vital to assess and manage these resources in a sustainable manner within an integrated water resource management approach. Transboundary aquifer assessments have largely focused on the regional scale which is not sufficient for countries to manage their transboundary aquifers effectively. This paper focuses on results of a national transboundary aquifer unit assessment in Malawi as a case study to support the countries plans for achieving Sustainable Development Goal 6.5.2.

New hydrological insights for the region: We have identified 38 new transboundary aquifer units shared between Malawi and its neighbours. These results can form the basis for future transboundary aquifer management between Malawi and its neighbouring countries. We also highlight the current limitations of transboundary aquifer assessments and management that should be addressed to achieve SDG 6.5.2. These include institutional mechanisms, limited cross-border data sharing, limited groundwater monitoring, and a need to revisit the wording of the transboundary-focused SDG target and its indicators.

Key Words

Transboundary, Aquifer, Groundwater, Sustainable Development Goals, Africa, Malawi

5.3 Introduction

Over 783 million people across the globe do not have access to an improved source of drinking water, 40% of which live in Sub-Saharan Africa (UNDESA, 2016). Sustainable development and management of this vital resource is essential as exemplified in the recent adoption of the Sustainable Development Goals (SDGs) by the United Nations in September 2015. Goal 6 of the SDGs is to ensure the availability and sustainable management of water and sanitation. Target 6.5.2 in particular recognises the importance of integrated water resource management and furthermore, identifies that transboundary cooperation can play an important role in this (UN Water, 2015).

Transboundary aquifers have long been known to store and transmit large volumes of groundwater from one country (or state) to another. It is important to identify those groundwater aquifers that may be transboundary in order to manage them effectively in conjunction with surface water within an IWRM framework. TBA assessments internationally have been largely focused on the regional scale (ILEC et al., 2016; Rivera and Candela, 2018). There are exceptions such as the Milk River Formation between Canada and the United States (Petre et al., 2016; Petre et al., 2015), the Guarani Aquifer System, and the Ramotswa and Stampriet Aquifer Systems (Dos les cobs, 2018; Nijsten et al., 2018). The main driving force for international TBA assessments is the UNESCO-IHP (United Nations Educational, Scientific and Cultural Organization - International Hydrological Programme) through the Internationally Shared Aquifer Resources Management (ISARM) initiative and the International Groundwater Resources Assessment Centre (IGRAC). IGRAC publishes a ‘Transboundary Aquifers of the World’ map with all known TBAs displayed, based on the most recent inventory results from projects globally. This compilation of international data constitutes a valuable starting-point for governments. A large proportion of TBAs within Africa were identified through the ‘Global Environment Facility Transboundary Waters Assessment Program’ (GEF-TWAP) regional assessments (ILEC et al., 2016). The aim of the GEF-TWAP was to provide the first global scale assessment of transboundary waters. GEF-TWAP regional assessments were carried out by an appropriate representative from each country then collected and streamlined by the project.

It is estimated that 40% of the world's population relies on transboundary groundwater as their primary drinking supply. Management, however, of TBAs, is still within its infancy both at a national and international level. Out of 592 TBAs identified worldwide, only 6 have an agreement governing their use and management (Rivera and Candela, 2018). Within Africa, the GEF-TWAP identified 80 TBAs. Of this 80, only 1 TBA has an agreement governing the use of it. Transboundary management is important in Africa as 75% of the continent relies solely on groundwater as its primary water supply for agriculture, irrigation and drinking (Altchenko and Villholth, 2013). In order to manage these resources properly, sufficient transboundary aquifer assessments must be carried out. These often require substantial data sets and financial resources that are not always available to regions with low economic income, as is the case for a large proportion of Africa.

Fraser et al., (2018) advocates for countries to conduct a full national border based assessment of transboundary aquifers at both local and national scale in order to more directly apply transboundary associated sustainable integrated water resource management. Within Malawi, a landlocked country in the south eastern region of Africa, there was a need to identify TBA units to support the government with water resource management while setting goals to achieve SDG 6.5.2. Malawi as a case study could be representative of other countries with similar financial circumstances or hydrogeology characteristics. With less than 1,400m^3/year of available total renewable water resources per person (Fraser et al., 2018), Malawi is also one of the most water stressed countries in the world, more so than Botswana and Namibia, countries that contain large areas of desert within them. With its growing population of 2.9% per year, climate change, and land degradation, the total available renewable water resources will decline further (Government of Malawi, 2018). By identifying all potential transboundary aquifer units that cross Malawi's international borders shared with Zambia, Tanzania and Mozambique, management strategies can be employed to target vulnerable areas and populations.

The understanding of Malawi's groundwater resources is still within its infancy. Although aquifer delineation has been conducted and productivity is well understood, specific characteristics including aquifer thickness, depth to water table, recharge and discharge zones, connectivity to surface waters, groundwater flow direction, groundwater contamination, natural groundwater quality etc. are either not reported or poorly understood to an appropriate level for sustainable management. This makes the challenge of identification and descriptions of transboundary aquifers even more challenging.

Moving forward on national based transboundary aquifer assessments, our work in evaluating the significance of local transboundary groundwater, seeks to account for the expected discontinuous nature of the basement complex arising from the complex comprising of multiple lithologies, and will consider the differences between the weathered and fractured zones within the basement complex to evaluate the significance of transboundary groundwater exchange (Fraser et al., 2018). Finally, a discussion of limitations to transboundary aquifer assessments both within the developing world context and internationally is presented. We highlight multiple challenges that must be addressed moving forward to achieve more reliable and detailed TBA assessments. The aims within the paper are thus to:

- Present the results of a national border based assessment of Malawi's transboundary aquifer units.

- Describe the identified transboundary aquifer units shared between Malawi and its neighbours alongside data gaps that will require addressing to move forward.

- Present a discussion of methodology limitations identifying issues such as cross border data harmonization and mapping consistency.

- Discuss the implication of these results within the SDG agenda

5.4 Methodology

The approach used for this study was to collect and synthesise all available literature and data relating to the transboundary aquifers shared between Malawi and its neighbours and to then create an initial interpretation of the TBAs along the entire Malawian national border that can provide a foundation for future more directed work. It is the first of its kind to assess transboundary aquifers across all of a countries international borders at one scale using the same method. Geological and hydrogeological maps have been used alongside literature and raw data in order to build a coherent picture of Malawi's transboundary aquifer situation. Building on the previous regional TBA assessment (IGRAC and UNESCO, 2015b) through the GEF-TWAP, this study aims to provide a more detailed review of transboundary aquifers as a starting point for national scale and localised management. It is important to note this interpretation only accounts for land based aquifers and thus the potential transboundary aquifer units that reside partly under Lake Malawi have not been identified due to the lack of geological or hydrogeological data underneath Lake Malawi.

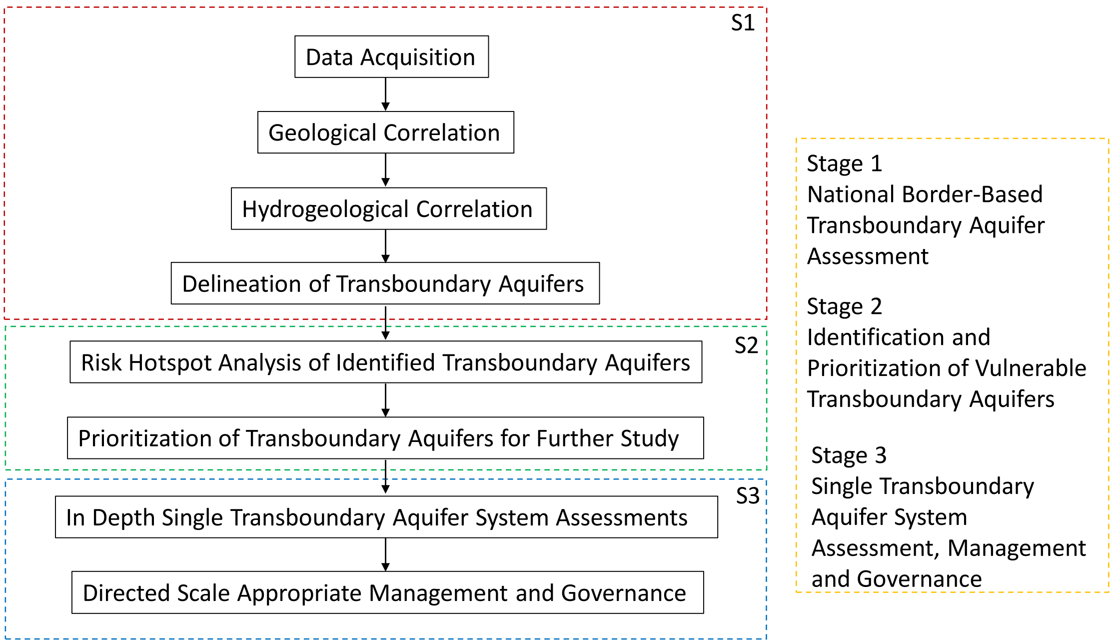


Figure 5.1 - Assessment framework for transboundary aquifers

Figure 5.1 has been developed to underline the process of national border based transboundary aquifer assessments within an overall framework for assessing transboundary aquifers within a single country for multi-scale management. This study represents stage 1 of the process, with future research and work needed to complete stages 2 and 3.

5.4.1. Geological and Hydrogeological Correlation

The common hydrogeological principle that aquifers are defined by lithology changes was adopted. To interpret which aquifer units within Malawi crossed its international borders, Malawian geological maps (1: 250,000 scale, Geological Survey of Malawi, 1970) and hydrogeological maps (1: 250,000 scale, Government of Malawi, 1987) were georeferenced in QGIS and aligned with Mozambique hydrogeological maps (1:1,000000 scale, Ferro & Bouman, 1987a and b), Zambia geological and productivity maps (1: 1,000,000 scale, Geological Survey Department of Zambia, 1975; Deltares and Aurecon, 2016) and finally Tanzanian geological maps (1:125,000 scale, Geological Survey of Tanzania, 1953). Correlated geological lithological units between Malawi, Mozambique, Zambia and Tanzania are provided in Appendix B. Cross border geological harmonization although effective has some limitations and multiple assumptions were made in order to interpret the geological and hydrogeological data. Different methods of naming geological formations caused confusion and different scales of available data meant interpretation was required at some points. Although this methodology provides a starting point for resource limited countries to initially assess their TBAs, If TBA assessments are to improve and assist in the achievement of SDG 6, significant investment will have to be made in order to minimise the assumptions and limitations in future analysis.

To conduct the geological and hydrogeological harmonization effectively, multiple assumptions were needed and refining of these assumptions with further data would naturally allow for updated interpretation. The assumptions are:

- A water bearing geological unit as identified by any country, if transboundary, is assumed to also be water bearing in the neighbouring country and potential for cross border flow of groundwater exists.

- Where possible, the basement complex has been subdivided into different lithologies, however due to limited data in Zambia, this was not always possible. Where not possible, weathered/fractured basement units are separated in Malawi and assumed to continue into Zambia.

- Mineral composition of different basement complex units mean they weather differently thus creating different aquifer properties.

5.4.2 Transboundary Aquifer Delineation

Known water bearing units were identified, and those that crossed Malawi's international border were assigned details of lithology, average yield and productivity. Where aquifer units crossed Malawi's border and matching geology and hydrogeology conditions within the neighbouring country existed, this was deemed to be a transboundary aquifer unit. Hydrogeological characteristics of each aquifer were then identified including lithology, surface area extent, productivity, potential surface water connections, water quality and finally, groundwater flow direction using piezometric surface maps.

5.4.3 Data Gaps

Data gaps were noted upon identification and description of the transboundary aquifers. In many of the sparsely populated areas of Malawi and its neighbours, literature on groundwater quality and availability was limited. A lack of monitoring boreholes throughout Malawi and its neighbouring countries makes it difficult to establish if groundwater levels along the borders are depleting. Advancements in mapping and geological and hydrogeological understanding in Malawi may allow re-interpretation in support of SDG 6.

5.5 Results

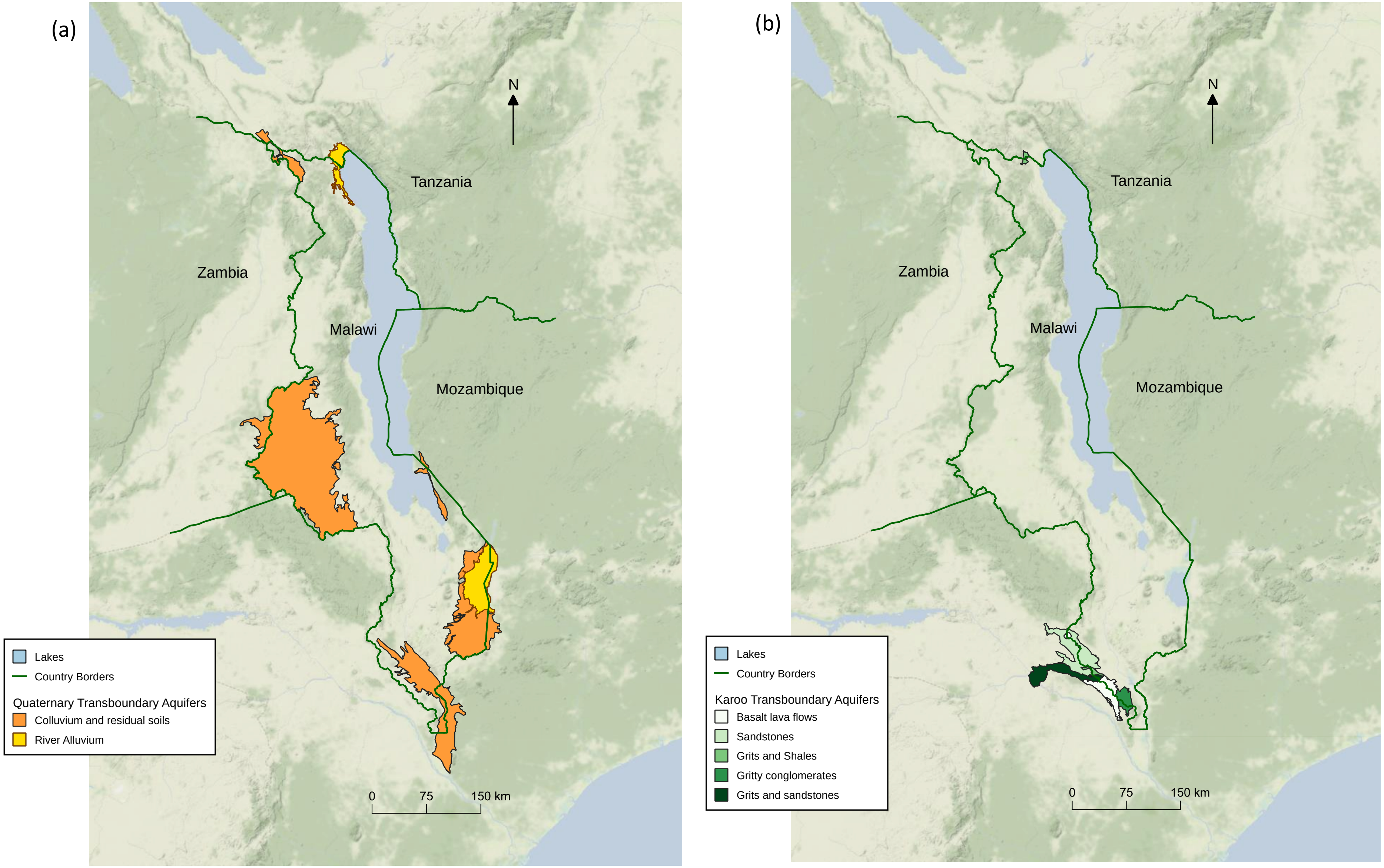
Results indicate that there is a total of 38 transboundary aquifer units shared between Malawi and its neighbours (Figure 5.2 and 5.3). 26 of these TBAs are with Mozambique, 2 with Mozambique and Zambia, 4 with Zambia, 3 with Zambia and Tanzania and finally 3 with Tanzania. Malawi shares most of its transboundary aquifers with Mozambique and the least with Zambia. The aquifers hydrogeology ranges in productivity and the large majority of Malawi is covered in low yielding basement aquifers. There are however multiple smaller high yielding aquifers formed from alluvial and Karroo deposits that form productive and important local water sources.

5.5.1 Geological and Hydrogeological Correlation

The geology and hydrogeology of Malawi and its neighbouring countries has been previously described (Fraser et al. 2018; Smith-Carrington and Chilton, 1983; Upton, 2016). The TBAs range in lithology's encompassing Weathered Basement Complex, Fractured Basement Complex, the Karoo Sediments, the Karoo Basalts and Quaternary Alluvial Deposits (figure 5.2). As expected, the large majority of Malawi's aquifers are transboundary due to the small size of the landlocked nature of Malawi. A gap within central Malawi can be seen in figure 5.3 where there have been no identified TBAs as many of the aquifers within this area are small and localised and the little is known of the hydrogeology under Lake Malawi. A stratigraphy column detailing geological correlation is provided in Appendix B.

5.5.2 Transboundary Aquifer Unit Descriptions

The identified transboundary aquifers are summarised in table 5.1, separated by aquifer type and assigned a unique TBA number. Each aquifer type is described as follows.


(a)
N
Tanzania
Zambia
Malawi
Mozambique
Lakes
Country Borders
Quaternary Transboundary Aquifers
Colluvium and residual soils
River Alluvium
0
75
150 km
(b)
N
Tanzania
Zambia
Malawi
Mozambique
Lakes
Country Borders
Karoo Transboundary Aquifers
Basalt lava flows
Sandstones
Grits and Shales
Gritty conglomerates
Grits and sandstones
0
75
150 km

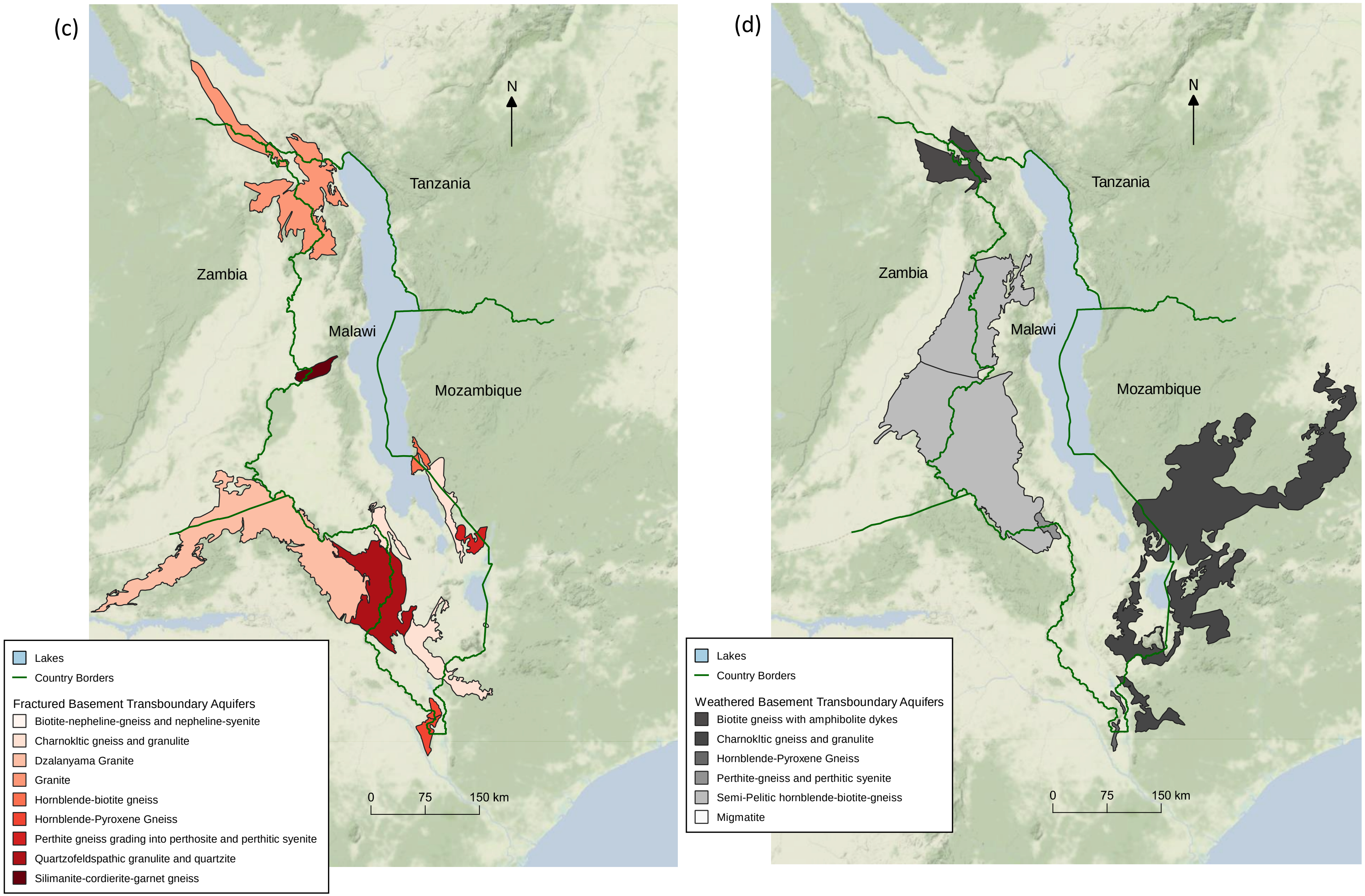


Figure 5.2 a, b, c and d - Transboundary Aquifers of Malawi, separated by lithology and type

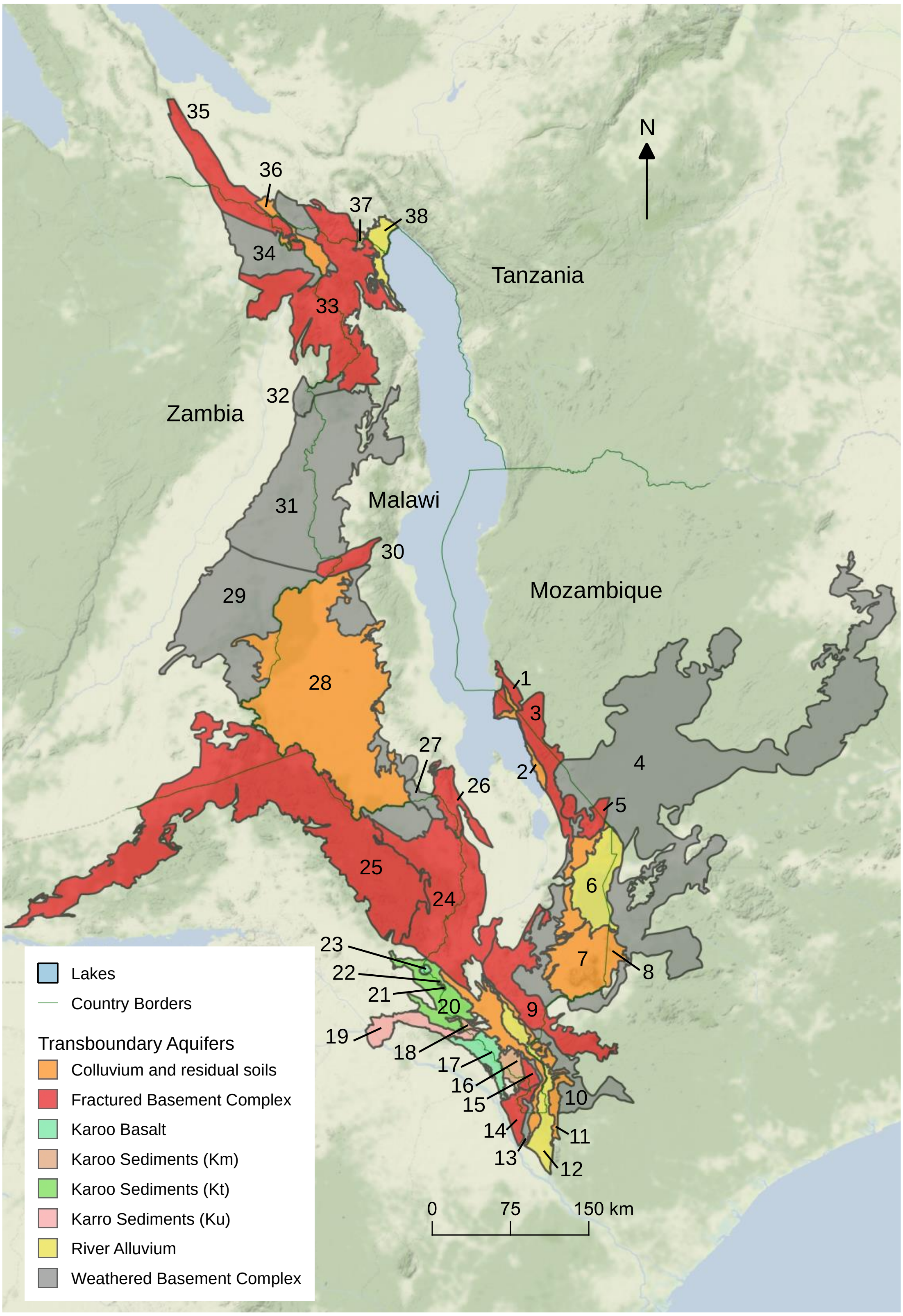


Figure 5.3 - Combined map of transboundary aquifers shared between Malawi and it neighbours (aquifers are numbered and linked to table 5.1)

Table 5.1 - Summary of each identified transboundary aquifers hydrogeological details (Kelly et al., 2019a; Kelly et al., 2019b; Bath, 1990; Chavula 2012; Smith-Carington and Chilton, 1983; Habgood, 1964; Bradford, 1973; UN, 1989; Mkandawire 2004)

TBA Number	Geological Lithology	Aquifer Type	Shared With	Surface Extent (km^2)	Aquifer productivity	Water Table Depth (m)	Surface Water Connections	Transmissivity (m^2/day)	Hydraulic Conductivity (m/d)	Groundwater Flow Direction	Other Information
1	Hornblende-biotite gneiss with graphite	Fractured Basement	Mozambique	628.2	Low to moderate	15-25	No Data	5-35	0.5-1.5	Mozambique to Malawi (northwest)	Extends up to and potentially into Lake Malawi
2	Colluvium and residual soils	Superficial	Mozambique	480.4	High to very high	5-10	No Data	50-300	1-10	Mozambique to Malawi (northwest)	Unconfined
3	Charnockitic gneiss and granulite	Fractured Basement	Mozambique	2082.7	Low to moderate	15-25	No Data	5-35	0.5-1.5	Mozambique to Malawi (northwest)	Groundwater of these aquifers tend to be of good quality
4	Charnockitic gneiss and granulite	Weathered Basement	Mozambique	37313.1	Low to moderate	15-25	Ruo River	5-35	0.5-1.5	Mozambique to Malawi (northwest)	
5	Perthite gneiss grading into perthosite and perthitic syenite	Fractured Basement	Mozambique	916.5	Low to moderate	15-25	No Data	5-35	0.5-1.5	Mozambique to Malawi (northwest)	
6	River alluvium	Superficial	Mozambique	2853	High to very high	5-10	No Data	50-300	1-10	Malawi to Mozambique (east)	Alluvial aquifers can exhibit high chloride salinity levels due to mineralization
7	Colluvium and residual soils	Superficial	Mozambique	7791.2	High to very high	5-10	Ruo River	50-300	1-10	Malawi to Mozambique (east)	
8	Nepheline-syenite	Fractured Basement	Mozambique	31.6	Low to moderate	15-25	No Data	5-35	0.5-1.5	Malawi to Mozambique (east)	
9	Charnockitic gneiss and granulite	Fractured Basement	Mozambique	3849.2	Low to moderate	15-25	No Data	5-35	0.5-1.5	Malawi to Mozambique (south)	
10	Charnockitic gneiss and granulite	Weathered Basement	Mozambique	1784.1	Low to moderate	15-30	No Data	5-35	0.5-1.5	Malawi to Mozambique (south)	High fluoride and Iron content in groundwater
11	Colluvium and residual soil	Superficial	Mozambique	4966.6	High to very high	5-10	No Data	50-300	1-10	Malawi to Mozambique (south)	
12	River alluvium	Superficial	Mozambique	1930.3	High to very high	5-10	Shire River and tributaries	50-300	1-10	Malawi to Mozambique (south)	Recharge in east of aquifer more than 2000 mm/yr. High

											Fluoride, and chloride salinity in lower Shire.
13	Hornblende-pyroxene-gneiss	Weathered Basement	Mozambique	228.5	Low to moderate	15-30	No Data	5-35	0.5-1.5	Malawi to Mozambique (south)	
14	Hornblende-pyroxene-gneiss	Fractured Basement	Mozambique	774.8	Low to moderate	15-25	No Data	5-35	0.5-1.5	Malawi to Mozambique (south)	
15	Hornblende-pyroxene-gneiss (partly garentiferous)	Fractured Basement	Mozambique	332.7	Low to moderate	15-25	No Data	5-35	0.5-1.5	Malawi to Mozambique (south)	
16	Mwanza gritty conglomerates	Karoo Sediments (Km)	Mozambique	576.4	Low to moderate	20-30	No Data	No data	No data	Malawi to Mozambique (south)	
17	Basalt lava flow	Karoo Basalt	Mozambique	1065.7	Moderate	Unknown	No Data	No data	No data	Malawi to Mozambique (south)	Fault bound on the Malawi side. Intrudes through the Karoo Sediments
18	Mwanza grits and shales	Karoo Sediments (Km)	Mozambique	134.2	Low to moderate	20-30	No Data	No data	No data	Malawi to Mozambique (south)	
19	Upper sandstones (grits and sandstones)	Karoo Sediments (Ku)	Mozambique	1283.4	Low to moderate	20-30	No Data	No data	No data	Malawi to Mozambique (south)	
20	Lower sandstones	Karoo Sediments (Kt)	Mozambique	2283.8	Low to moderate	20-30	No Data	No data	No data	Malawi to Mozambique (south)	Oldest Karoo Sediments. Potential for deep fossil aquifers.
21	Mwanza grits and shales	Karoo Sediments (Km)	Mozambique	11.4	Low to moderate	20-30	No Data	No data	No data	Malawi to Mozambique (south)	Karoo aquifers tend to be fairly unexplored in this region
22	Mwanza grits and shales	Karoo Sediments (Km)	Mozambique	8.4	Low to moderate	20-30	No Data	No data	No data	Malawi to Mozambique (south)	
23	Basalt lava flow	Karoo Basalt	Mozambique	67.3	Moderate	Unknown	No Data	No data	No data	Malawi to Mozambique (south)	
24	Quartzofeldspathic granulite and quartzite	Fractured Basement	Mozambique	8616.7	Low to moderate	15-25	No Data	5-35	0.5-1.5	Mozambique to Malawi (southeast)	
25	Granite (dzalanyama)	Fractured Basement	Mozambique and Zambia	21136.3	Low to moderate	15-25	No Data	5-35	0.5-1.5	From Zambia and Malawi to Mozambique (southeast)	
26	Charnockitic gneiss and granulite	Fractured Basement	Mozambique	1478.9	Low to moderate	15-25	No Data	5-35	0.5-1.5	Mozambique to Malawi (east)	High sulphate in Salima sub catchment, caused by gypsum saturation
27	Perthite-gneiss and perthitic syenite	Weathered Basement	Mozambique	595.0	Low to moderate	15-25	No Data	5-35	0.5-1.5	Mozambique to Malawi (east)	

28	Colluvium and residual soils	Superficial	Zambia	18815.3	High to very high	5-10	Bua Catchment	50-300	1-10	Zambia to Malawi (east)	Iron problem in weathered basement complex in Bua Catchment of up to 59mg/l
29	Biotite-gneiss with garnet in parts	Weathered Basement	Mozambique and Zambia	31640.7	Low to moderate	15-25	No Data	5-35	0.5-1.5	Zambia to Malawi (east)	
30	Silimanite-cordierite-garnet gneiss	Fractured Basement	Zambia	891.2	Low to moderate	15-25	No Data	5-35	0.5-1.5	Zambia to Malawi (east)	
31	Semi-pelitic hornblende-biotite-gneiss	Weathered Basement	Zambia	14089.0	Low to moderate	15-25	No Data	5-35	0.5-1.5	Zambia to Malawi (east)	High chloride salinity recorded up to 2000mg/l in South Rukuru
32	Magmatite	Weathered Basement	Zambia	816.4	Low to moderate	15-25	No Data	5-35	0.5-1.5	Zambia to Malawi (east)	
33	Granite	Fractured Basement	Zambia and Tanzania	13621.3	Low to moderate	15-25	No Data	5-35	0.5-1.5	Mozambique to Malawi (east)	
34	Biotite gneiss with amphibiotite dykes	Weathered Basement	Zambia and Tanzania	4476.0	Low to moderate	15-25	No Data	5-35	0.5-1.5	Zambia to Malawi (east)	
35	Granite	Fractured Basement	Zambia and Tanzania	13621.3	Low to moderate	15-25	No Data	5-35	0.5-1.5	Runs along border to the east	
36	Colluvium and residual soils	Superficial	Tanzania	883.9	High to very high	5-10	No Data	50-300	1-10	Runs along border to the east	
37	Mwanza grits and shales	Karoo Sediments (Km)	Tanzania	113.5	Low to moderate	20-30	No Data	No data	No data	Runs along border to the east	
38	River alluvium	Superficial	Tanzania	34.0	High to very high	5-10	No Data	50-300	1-10	Malawi to Tanzania (east)	Extends up to and potentially into Lake Malawi

5.5.2.1 Unconsolidated Aquifers

The unconsolidated aquifers are composed of alluvial and colluvium lithologies. There are a total of 3 alluvial transboundary aquifers and 5 colluvial aquifers that extend across Malawi's borders (figure 5.2c). Often lying unconformably on top of other lithologies, these aquifers are the youngest within Malawi. The unconsolidated transboundary aquifers of Malawi are widespread across the country, most reside in the south of Malawi shared with Mozambique, and there is 1 colluvium aquifer shared in the central region with Zambia and another 2 in the north. These aquifers tend to be small compared to larger basement aquifers but are the most highly productive. Quaternary alluvial deposits are composed of clays, silts, sands and gravels, deposited in the floor of the East African Rift System (EARS) rift valley and along river plains (UN 1989). The lithology of the deposits is highly variable (heterogeneous and anisotropic). The composition changes considerably over short distances due to the nature of their deposition from outwash fans, floor plains and river channels (Mkandawire, 2002). The mineral assemblages of these alluvium suggest that they are derived from the Precambrian Basement Complex, primarily from the gneiss (Habgood 1963). The presence of clays means that good yields with high water quality is only present within the gravel beds of the units where permeability is good (Habgood, 1963) and artesian water pressures may exist in places due confinement below clay layers. The depth of saturation within these aquifers varies seasonally. The water table depth is typically between 5 and 10 meters below ground (Chavula 2012) and thickness can range from 40 to 150 meters (UN 1989; Smith-Carrington and Chilton. 1983). The transmissivity ranges from 50 to 300 meters^2/day, hydraulic conductivity for sands and gravels is between 10 to 20m/day. Specific yield ranges between 3 to 10% (Smith-Carington and Chilton, 1983). The alluvial deposits are recharged through rainfall, which is spatially variable depending on location. Some additional recharge also comes from seepage of riverbeds that are permeable (Kelly, 2019b). These aquifers are unconfined when colluvium do not cover them.

Lying on alluvial deposits and weathered basement colluvium is also found. These are superficial deposits of residual soils formed by soil creep. These are commonly thin deposits, but are quite extensive across Malawi. Hydraulic conductivity for the poorly sorted clayley and colluvial sands ranges between 1 to 5 m/day with specific yield ranging between 3 to 10% (Smith-Carington and Chilton, 1983).

5.5.2.2 Karoo Sequence

Within the western portion of the Shire River Basin in the southwest of the valley, a small section of Transboundary Karoo Sequence rocks exist. There are a total of 8 aquifers here composed of a combination of both basalts and sedimentary units (figure 5.2d). Many of these aquifers are localised. They lie unconformably on crystalline basement and are fault bound on the Malawi side of the border due to the influence of the EARS (Ferro & Bouman, 1987). In the north, there is 1 other transboundary Karoo sedimentary aquifer shared with Tanzania.

The Karoo Stormberg Volcanics represent the upper part of the Karoo Sequence. They encompass a series of microporphyritic to glomeroporphyritic tholeiitic basaltic lava flows (Dill, 2007) often interbedded with bands of sandstone (Habgood, 1963). Permeable and porous layers exist between consecutive lava flows interbedded with layers of sandstone and tuff (UN 1989). The flows are often vesiculated towards the top of top, and in-filled with calcite and quartz (Habgood, 1963). Within the centre of the Karoo weathered basalts, the unit is impermeable, however because of interstitial spaces at contacts between flow, there are zones where permeability is very high. This is due to vesicular cavities providing a flow path for the water (Habgood, 1964). Furthermore, jointing and faulting of the lava flows has resulted in fracturing that increases permeability further. Groundwater movement through the basalts is fairly rapid as illustrated through the high quality and low mineralization of the water with yields, above 1.1l/s (Habgood, 1964). These may form moderate productivity local aquifers.

The Karoo sedimentary rocks can be subdivided into three distinct units; The basal beds composed of conglomerates and sandstones; a sequence of sandstones, mudstones, shales and coal seams in the middle; and grits, arkose sandstones, shales, mudstones and marls in the upper section. The upper successions tend to be cemented by calcite and the primary porosity is low. Permeable horizons are related to secondary fracturing. The Karoo Sediments are thought to have an estimated thickness of 500 meters (Bradford, 1973; UN 1989).

The Karoo sedimentary rock outcrops tend to be relatively small and not vastly abundant. Despite this the units tend to exhibit high permeability and tends to be highly fractured. The rocks of the Karoo are generally well-cemented with low porosity and intergranular permeability. Groundwater storage and flow occurs largely in fractures in the rocks. Groundwater levels are typically 20 m to 30 m below ground surface (UN 1989). These rocks may form a low to moderate productivity local aquifer. The groundwater quality of the Karoo sediments tends to be highly variable depending on location and depth ranging from freshwater to extremely saline water. Within the south of Malawi, the Karoo aquifers tend to be either dominated by calcium carbonate or sodium chloride influenced water types.

5.5.2.3 Fractured Basement Complex

There are 13 unique sub-sets of fractured basement complex transboundary aquifers identified within this study. They extend across the entire of Malawi predominantly in the centre of the country along the border shared with Zambia and along the southeast border shared with Mozambique (figure 5.2a).

Precambrian crystalline basement rocks are gneiss and granulite with some metamorphic schists, quartzites and marbles (UN 1989). The basement complex is intruded by dykes and other igneous lithologies. (UN 1989). The large majority of Malawi is underlain by these rock units that have undergone several deformation and metamorphic phases that has affected large areas of Africa (Caman et al., 1969). Due to their resistance to erosion they often form much of the elevated regions in Malawi. In the north and west of Malawi, the basement complex exists as lower grade metamorphic rocks, those in the south were originally mudstone, sandstone and conglomerates. It is most likely that these rocks are from a sedimentary origin pre metamorphism (Bloomfield, 1968). Due to recrystallization during deformation, the basement rocks have been rendered with both low primary porosity and permeability.

The fractured basement complex aquifers store groundwater in fractures (secondary porosity) associated with geologically weak zones, easily disintegrated into individual blocks, bounded by fractures and joints (Fraser et al., 2018). These zones are associated with particular geological structures like folds, faults and fractures displaying relatively high permeability. Along dikes intruding the basement complex, aquifers can also develop in the fracture zone on the contact between the intrusive body and the adjacent rocks. The un-fractured parts of the dikes often form impermeable barriers (Ferro & Bouman, 1987).

It is probable that the basement complex aquifers provide baseflow for many of the country's surface watercourses and despite the semi-confined nature of the surface clays, recharge is most likely to come in the form of rainfall infiltration (Kelly, 2019a; Kelly, 2019b; Smith Carrington and Chilton, 1989). Conductivity borehole logging and analysis of boreholes tapping the basement complex aquifer suggests water quality layering within the units. Distinct layering with considerable lateral variation is evident suggesting that there may be more than one water type within some aquifers. Furthermore, in some localised areas, there is evidence of mixing of these different water types (Smith Carrington and Chilton, 1983).

These units tend to yield 0.5-0.8l/s from around 30-45meter depths. This is often enough to supply local villages but not regional areas (Habgood, 1964). The water acquired is of good quality with low salinity. Often, these aquifer units are not reached when drilling due to being too deep resulting in high expense (Habgood, 1964, Kalin 2019). Locally, some parts of the aquifer units do tend to exhibit saline water, this does not appear to be related to the rock composition and is more likely caused by evaporation and mineralization along fault zones (Rivett 2018c). Overall, the units do tend to exhibit low mineralization regionally and this suggests that recharge is recent.

Fractured basement complex lithology's are discontinuous resulting in local aquifers as opposed to large scale regional aquifers (Fraser et al., 2018). Although low yielding, these aquifers are often an important local groundwater resource and therefore must be considered locally within the context of Sustainable Development Goal 6.

5.5.2.4 Weathered Basement Complex

There are 8 weathered basement complex aquifers shared between Malawi and its neighbours. These saprolitic units range in size from smaller more local scale aquifers in the very south and north of Malawi to larger more regionally significant aquifers in the south east (figure 5.2b). Formed of the same geological lithologies as the fractured basement aquifers, the weathered aquifers differ in the type of secondary saprolitic porosity exhibited to store water. The process of weather involves the breakdown of the bedrock through chemical and physical factors. The occurrence of coarse grained or heterogeneous rocks as well as soluble marbles, or the existence of contacts between rock types of different nature also facilitate weathering. The weathered basement aquifers are best developed in topographical highs within Malawi (Smith-Carrington and Chilton, 1983). It can be divided into 3 distinctive layers: the laterite layer which is composed of mainly red clay or completely weathered silt; the saprolite layer which is composed of quartzitic clayey sand or heavily weathered fine to coarse sand; and a medium weathered layer in which rock mass is separated into fragments or small blocks by groundwater infiltrating into joints of rock (Zauyah et al., 2010; Smith-Carrington and Chilton. 1983). The best yielding layer is the medium saprolite layer and it occurs between 15-30 meters. The aquifer thickness or the occurrence depth is very variable due to topographic conditions. Weathering is controlled by the rock type and structure, slope, regional climate, lithology and mineral type, the spacing between joints and the degree of rock mass (Spellman and Stoudt, 2013; Smith-Carrington and Chilton, 1983; UN, 1989). As an example, gneiss and granulites are coarse grained with quartz minerals. Weathering of these units provides a good water bearing capacity. Schist, syenite and gabbro on the other hand exhibit clay minerals and poor water bearing capacities (Smith-Carrington and Chilton. 1983). Weathered basement aquifer transmissivities are generally in the range of 5 to 35 m^2/day with estimated hydraulic conductivities ranging from 0.01 to 1 m/d. The storage coefficient, on the other hand, has been assumed to range from 0.01 to 0.001 (Mkandawire 2004). These aquifers are under unconfined to confined conditions. Borehole yields are generally highest where the saturated thickness of the weathered zone is greatest and the parent bedrock coarsest (Chilton and Smith- Carington, 1984). In general, the weathered basement aquifer produces low borehole yields (Chilton and Smith-Carington, 1984).

5.5.3 Data Gaps

Although the basic hydrogeological characteristics of the transboundary aquifers are understood (table 5.1), a number of data gaps have been highlighted throughout this study. The lack of monitoring boreholes in place to monitor groundwater levels means that potential groundwater depletion within these aquifers is unknown. This makes it difficult to determine whether a transboundary aquifer is under stress or at risk of abstraction becoming unsustainable. There is also limited data available on the use of groundwater. Although it is well established that a large proportion of Malawi's rural communities rely on groundwater as their primary drinking water source, other uses of groundwater are poorly understood. Other vital information such as recharge and discharge zones of these transboundary aquifers are inadequately investigated. This will pose problems if Malawi and a neighbouring country were to want to foster an agreement over one of their shared aquifers as international recharge and discharge can play an important role in the conceptualisation of a transboundary aquifer and will direct the appropriate legal frameworks required to direct the aquifer agreement. Within Malawi, some studies have been done looking at the hydraulic connections that exist between groundwater and surface water however these are still in their infancy and still require further attention. Furthermore, evidence of groundwater contamination within these aquifers is only viable for those aquifers that have been tested; the assumption that no record of contamination means no contamination should not be taken.

Within Malawi there is also a north-south divide on the amount of research and field investigations done to assess and understand groundwater resources. The centre and south of Malawi is more densely populated than the north and this has contributed to the majority of research funding being directed in these areas. The Shire River Valley and its related river basins, aquifers and catchments are also an important water and energy supply in the region that has subsequently led to a focus on this area for research. The lack of data in the North of Malawi in relation to the south has resulted in a diminished understanding of the water resources in the North, which contributes to the shortage of transboundary understanding.

5.6 Discussion

The results of this study indicate that there are many more small-scale transboundary aquifers in Malawi, and likely across Africa than previously thought. This is important as current management structures in place within these countries often do not facilitate local scale transboundary management. Studies of this scale are also hindered by multiple limitations. Data availability is a major issue in many countries and this case study is not exempt as previously discussed. Alongside this, the detail of geological and hydrogeological maps that require harmonization across the border at this scale is much more complex resulting in increased difficulty in interpretation of aquifer units. Additionally, mapping consistence and different approaches to lithology delineation complicates harmonization further.

The importance of transboundary water management has been recognised within the Sustainable Development Goal agenda. Target 6.5.2 specifically refers to transboundary water; "by 2030, implement integrated water resources management at all levels, including through transboundary cooperation as appropriate" (UN Water, 2015). The nature of integrated water resource management demands both surface and groundwater to be considered in a holistic management approach (UN Water, 2017b). Historically the management of surface water has received comparatively more attention than groundwater (Eckstein and Sindico, 2014). This could be due to the simplicity in determining whether a lake or river crosses a political boundary, and the complexity of detailed study of hydrogeological units and groundwater flow. It is important to identify those groundwater aquifers that may be transboundary in order to manage them effectively in conjunction with surface water within an IWRM framework.

It can be argued the current SDG agenda for transboundary groundwater management is premature. This study alone shows that transboundary aquifers are still not understood at an effective level of detail for local management and national agreements. The expectation on countries to not only investigate, identify and establish a formal agreement over the use and management of these aquifers by 2030 appear to be a stretched target, especially given that only 6 formal agreements are currently in place over transboundary aquifers (Rivera and Candela, 2018). There is an inherent risk the SDG agenda will rush the transboundary aquifer identification process up and detail is missed. If detailed transboundary aquifer assessments like the one in this study are not undertaken, generalised regional assessments will be relied upon that may not be fit for purpose.

A key objective of the SDGs is 'Leave no one Behind', and therefore the localization of the policy and management of resources in line with SDGs must be a corner stone of national implementation strategies (UNCDP, 2018). Relying on generalised regional groundwater assessments will lead to poor or miss-management of the groundwater that are highly important at the local level. Transboundary aquifer assessments are also still restricted by data limitations, lack of cross-border data sharing, harmonizing cross border hydrogeological data, and limited groundwater monitoring practices (Fraser et al., 2018). Additionally, developing countries are faced with financial and capacity limitations that require national prioritisation under the SDGs which further inhibits TBA agreement development.

The wording of SDG target 6.5.2 leaves potential for gaps in the interpretation. The target calls for transboundary cooperation within Integrated water resource management at all levels as appropriate however the indicator for the target only measures the proportion of a transboundary basin area with an operational agreement (McCracken and Meyer, 2018). Firstly, groundwater aquifers do not necessarily follow surface water river basins and therefore the target has failed to identify this key differential (Fraser et al., 2018). Primarily focusing on the surface river basin level diminishes the importance of local cooperation of groundwater use by a substantial percentage of the population base. There is no guidance over what constitutes the need for transboundary cooperation within the SDG agenda and if there was, it would likely focus on reactive measures than proactive as integrated water resource management promotes reactive measures to water conflict instead of focusing on preventative approaches (Jarvis, 2010). Furthermore, some aquifers or indeed large areas of aquifers may not require an agreement over their use and management due to lack of usage or low dependency rates (Fraser et al., 2018).

The SGD 6.5 target indicator calls for the percentage of a basin under an operational agreement to be calculated. The term 'operational' requires any arrangement to include regular exchange of data, regular formal communication between parties, a joint management plan, and a joint body or mechanism to oversee the arrangement (UN Water, 2017a in McCracken and Meyer, 2018). Operational agreements of this manner and at this scale will require strong governance and institutions to implement them. Aligning the SGD indicators with already in-place institutional mechanisms will speed up this process. However, there are relatively few institutional mechanisms designed to manage transboundary groundwater resources. Often, these tools generally exist at the sub-national level (Linton & Brooks 2011; Feitelson 2003 in Ganoulis and Fried, 2018). In order to be effective, cooperation needs to happen at all scales. (UNESCO, 2016). Most examples of transboundary institutional mechanisms come in the form of joint bodies/commissions/committees created for river basin based cooperation. Case studies include (1) the International Commission on the Scheldt River that was set up to strengthen transboundary cooperation over the quality of the Scheldt River Basin District that runs through France, Brussels and the Netherlands (Machard de Gramont et al., 2001), (2) the Nile Basin Initiative that brings member states residing within the basin together for consultation and coordination of sustainable management and development of shared water within the basin (UN and UNESCO, 2018), (3) the Okavango River Basin Water Commission that established the Okavango Delta Management Plan through engaging with stakeholders such as communities of the delta, users of the resource, governments and management institutions (UN and UNESCO, 2018), (4) the Orange-Senqu River Commission formed following signing the 'Agreement for the Establishment of the

Orange-Senqu River Commission' between Botswana, Lesotho, Namibia and South Africa established to promote equitable and sustainable development of the resources of the Orange-Senqu River basin, including groundwater by proxy (UNESCO-IHP, 2016), (5) the North-South Ministerial Council that was formed as a response to the Belfast Agreement fostered between Northern Ireland and The Republic of Ireland that encourages cross-border cooperation between the two nations, including over shared water resourses (Fraser et al., 2020a). A common factor that is evident is that most institutional mechanisms that deal with transboundary groundwater governance are at the River Basin level, and have been initially driven by the desire for surface water management, with groundwater included as an addition. It is also often unclear within these mandates whether or not groundwater within the basin limits but not hydraulically connected to the surface waters are included (UNESCO-IHP, 2016).

Specific examples of effective institutional governance mechanisms dealing with just groundwater have developed as a consequence of international scale projects such as the 'Governance for Groundwater Resources in Transboundary Aquifers (GGRETA)' Project developing tools such as Multi-Country Cooperation Mechanisms (MCCM); a dedicated instrument to deal with transboundary groundwater management that can be nested within another institution. In GGRETA's case, within the Orange-Senqu River Commission (UNESCO-IHP, 2016). Similarly, the RAMOTSWA and Shire CONWAT project both utilise joint strategic action plans to identify and prioritise investment and actions that can be implemented for transboundary groundwater management with their respective regions (SADC-GMI, 2018; IWMI, 2019).

More pertinent to the Malawi case study, the Southern African Development Community has been progressive with its stance on transboundary water cooperation through its Water Division by developing a Regional Water Strategy that provides a strategic framework for sustainable use, protection and control of both national and transboundary water resources within the region, and the implementation of the Revised Protocol for Shared Watercourses (2000) that aims to foster close cooperation between member states over their shared water resources

(SADC, 2003). Most recently, the SADC-Groundwater Management Institute, a not-for-profit based in South Africa representing all SADC member states, was established to promote sustainable groundwater management within the region, build national and regional institutional capacity, lead national and regional coordination and improve knowledge management. A large part of its work is transboundary focused (SADC-GMI, 2018; IWMI, 2019).

93.2% of Malawi's territorial area and 86.1% of its population (MoAIWD, 2014) resides within the Zambezi River Basin and is party to the ZAMCOM Agreement; an agreement that sets out to foster cooperation from riparian states over the transboundary management of the surface water and groundwater within the basin (SADC-DW/ Zambezi River Authority, 2008). Moving forward, an option for this commission may be to set up a hydrogeological working group that can represent transboundary groundwater issues at the international level. An effective working example of this is the ORASECOM hydrological group within the commission (Nijsten, 2018). Although almost all of their transboundary aquifers reside within this transboundary basin, Malawi is yet to accede the ZAMCOM agreement into policy (ZAMCOM, 2019). It must do so in order to move forward with transboundary cooperation at the binational level.

These institutional frameworks discussed must be underpinned by local scale mechanisms. Local stakeholder involvement and local scale governance mechanisms are vital as those involved are often closest to the problem at hand and most impacted by poor resource management (Moench et al., 2012). The most common local-scale water governance mechanism is 'Community Based Management' (CBM) (Whaley et al., 2019). The CBM model is based on the concept of the local community managing their own water resources, often through the maintenance of water points such as hand-pumped boreholes. CBM was initially intended to provide a sense of ownership through local participation through Water Point Committees (Benito et al., 2010) and account for decentralised governmental systems in many areas of Africa (Truselove et al., 2019). However, research has suggested that the burden and services contained within CMB cannot be sustained long-term and that there is an issue of meeting the SDGs and sustainable financing for maintenance under a CBM approach (Truselove et al., 2019; Truselove et al., 2020). Community based management is also rarely seen at the formal transboundary level. Any transboundary cooperation is often informal and thus unrecorded and rendered ineffectual for the SDG mandate.

As previously noted, many of Malawi's transboundary aquifers are localised and therefore generalised policies at international basin level are not appropriate. In these cases, national policy that supports local level IWRM management strategies would be more effective. Moving forward, it may also be practical to identify particular vulnerable areas of transboundary aquifers that require management, rather than choosing to manage an entire aquifer. SDG 6.5.2 will require a formal agreement, and it is vital these recognise local dependence and vulnerabilities, without the approach presented here, generalised transboundary agreements will likely hinder local level development progress.

5.7 Conclusions and the Way Forward

The adoption of the Sustainable Development Goals has driven forward the importance of localisation of policy, planning, and management, and for goal 6, the need for sustainable and integrated transboundary aquifer management. This paper presents an approach to transboundary aquifer assessment at local level that supports Malawi (as a case study) and other countries to assess their border for transboundary aquifers shared with neighbours. It relies on the use of detailed geological and hydrogeological data alongside literature and groundwater studies. In Malawi, 38 transboundary aquifers of local to national importance were identified as being shared between Malawi and its neighbouring countries, an increase from the previous 3 identified, demonstrating the complexity lost in regional scale assessments. These aquifers vary in lithology, productivity and extent across the country, but all are locally important for water access to rural populations, local agriculture, and sustainable water resources. The assessment took into account the discontinuous nature of the basement complex arising from the complex comprising of multiple lithologies, and the differences between the weathered and fractured zones within the basement complex. These results form the basis for future transboundary aquifer studies, and discussions around management and agreements between Malawi and its neighbouring countries to set targets to achieve SDG 6.

Moving forward, it will be important to ensure that local-level transboundary aquifer assessments inform SDG 6.5.2. It will also be essential to ensure that specific vulnerable areas or ecosystems, or populations using these aquifers, are identified, monitored, and managed effectively. This could be in the form of zoning or potentially geospatial GIS hotspot analysis. It will also be important to consider that large scale aquifers likely have smaller areas of concern that require management and that these are likely to reside close to the border and have a community level impact. Engaging these stakeholders and building capacity in these areas will be essential for local scale management.

5.8 Postface

This chapter answered RQ2 ‘Are there more transboundary aquifers than previously thought in Malawi?’. It did so by first presenting a methodology for border based transboundary aquifer assessments and applied it to the Malawi case study (SO4). In total, 38 transboundary aquifers were identified, a dramatic increase from the previous 3 identified. Descriptions of the transboundary aquifers within Malawi were presented (SO5) and the current limitations of transboundary aquifer assessments and management that should be addressed to achieve SDG 6.5.2 were discussed (SO6). These include institutional mechanisms, limited cross-border data sharing, limited groundwater monitoring, and a need to revisit the wording of the transboundary-focused SDG target and its indicators.

The next chapter will continue to use the Malawi case study to explore whether all transboundary aquifers require detailed assessments, management and agreements governing them. It will present a methodology for identifying hotspots within transboundary aquifers that may be vulnerable to the groundwater quality and quantity issues.

6 A Methodology to Identify Vulnerable Transboundary Aquifer Hotspots for Multi-Scale Groundwater Management[3]

6.1 Preface

The previous chapter (chapter 5) presented a methodology for a border based transboundary aquifer assessments and applied it to the Malawi case study. 38 new transboundary aquifers were identified and descriptions of each type were given. The chapter highlighted many limitations of transboundary aquifer assessments and management approaches that should be addressed to achieve SDG 6.5.2. The chapter then concluded that moving forward, it will be essential to ensure that specific vulnerable aquifers or areas of aquifers are identified and managed effectively. It was highlighted that geospatial GIS hotspot analysis could assist with this.

Continuing with the Malawi case study, this chapter explores whether all transboundary aquifers require detailed assessments, management and agreements governing them (RQ3). A methodology is presented for identifying hotspots within transboundary aquifers may be vulnerable to the groundwater quality and quantity issues (SO7). This method is then applied to the Malawi case study where we identify which of Malawi's transboundary aquifers should be prioritised for directed national and local level management based on vulnerability hotspot mapping. Results indicate that there are 11 local scale and 3 national scale hotspots of transboundary concern within Malawi (SO8). Engaging stakeholders and building capacity in these areas will be essential for multi-scale management. Finally, a discussion of the importance of multi-scale management approaches to transboundary aquifers highlighting ways in which institutional organizations and transboundary agreements and arrangements can assist in its implementation is given (SO9).

This chapter is a peer reviewed paper published within Water international.

Paper reference:

[3]Fraser, C.M., Kalin, R.M., Kanjaye, M., Uka, Z. 2020. A Methodology to Identify Vulnerable Transboundary Aquifer Hotspots for Multi-Scale Groundwater Management. Water International. 45:7-8, 865-883.

Author contribution:

Conceptualization (C.M.F, R.M.K), data curation (C.M.F, R.M.K), formal analysis (C.M.F), investigation (C.M.F), methodology (C.M.F.), validation (C.M.F., M.K., Z.U.), visualization (C.M.F.), project administration (R.M.K), supervision (R.M.K), writing original draft (C.M.F), review and editing (C.M.F., R.M.K.., M.K., Z.U.)

6.2 Abstract

38 transboundary aquifer units are shared between Malawi and its neighbouring countries. It is essential to prioritise those transboundary aquifers that require immediate attention. A methodology of identifying hotspots within the transboundary aquifers of Malawi that may be at risk to depletion or contamination has been developed. Results indicate that there are 11 local scale and 3 national scale hotspots of transboundary concern within Malawi. Fiscal and planning measures can now be taken to assess these areas in more detail, fostering transboundary cooperation between the involved stakeholders at both the local and national scale.

Key Words

Transboundary, Aquifer, Hotspots, Management, Africa, Malawi

6.3 Introduction

Groundwater is a vital natural resource accounting for 97% of the non-frozen freshwater resources available across the globe (IGRAC and UNESCO, 2015a). It provides almost half of the drinking water worldwide alongside 40% of the water used for irrigated agriculture and 33% for industry (Smith et al., 2016; UN Water, 2018). It is essential for sustaining ecosystems and providing baseflow to rivers (Kelly et al., 2019a). Climate change and increasing human impacts on the environment are putting pressure on groundwater resources, causing quality and quantity issues (UN Water, 2018). Over the last decade, groundwater abstraction has tripled and continues to increase at around 2%/year (Van der Gun, 2012). This issue is exacerbated in many parts of Africa, where groundwater is often the only reliable source of water. Up to 75% of the population on the continent relies on groundwater as their main source of drinking water (UNECA et al.., 2000). Groundwater is also essential in these areas for rural livelihoods such as livestock rearing and agricultural crop cultivation (Villholth, 2013 and Foster et al., 2008 in Nisanje et al., 2018). The importance of groundwater was recognised in the United Nations Sustainable Development Goals adopted in 2015. Goal 6 is dedicated to clean water and sanitation, including groundwater. Target 6.5 of goal 6 calls for the implementation of integrated water resource management, at a transboundary level where appropriate (Mccracken, 2017).

Both surface waters and groundwater can be transboundary, meaning that rivers, lakes and aquifers have the ability to store and transmit water across a state or border (Fraser et al., 2020b). Whereas transboundary surface waters have been extensively studied worldwide, transboundary aquifers have received much less attention (Rivera and Candela, 2018). Transboundary aquifer assessments are now becoming a more common practice across the globe due to substantial efforts from the Internationally Shared Aquifer Resources Management initiative (ISARM) though the International Association of Hydrogeology (IAH) and the United National Education, Scientific and cultural Organization (UNESCO) since 2000 (Rivera and Candela, 2018). There are currently around 600 transboundary aquifers identified worldwide and 80 in mainland Africa (IGRAC and UNESCO-IHP, 2015b). The identification and basic hydrogeological understanding of these aquifers has been driven by the need for transboundary aquifer management and agreements for these vulnerable shared resources (Nijsten et al., 2018; Rivera and Candela, 2018; Fraser et al., 2018).

A recent study that took a detailed and national-border based approach to transboundary aquifer assessments in Malawi indicate 38 transboundary aquifer units shared between Malawi and its neighbours in contrast to a previous estimate of 3 (Fraser et al., 2018; Fraser et al., 2020b). It is likely that other countries, like Malawi, exhibit many more transboundary aquifers than previously thought. As the number of identified transboundary aquifers increase around the world, the need to prioritise which aquifers receive available resources and funds for in depth assessment and specialised management will become essential. Inherently, not all transboundary aquifers are at risk for reduced quality and over abstraction. Identifying which aquifers require attention and which do not is essential under integrated water resources management and for the Sustainable Development Goal (SDG) agenda. Furthermore, classifying whether a transboundary aquifer requires local, national or international cooperation and management will allow the best policy instrument, legal agreements and management mechanisms to be selected.

Within this paper we present a methodology for identifying hotspots within transboundary aquifers that may be vulnerable to the groundwater quality and quantity issues. Asset management data collected as part of the Climate Justice Fund: Water Futures Programme were utilised in this study through a spatial analysis site selection technique to identify key areas within transboundary aquifers in Malawi that may be at risk. These areas of risk were then classified into local and national scale transboundary hotspots. Aided with this information, policy makers and governmental officials have the ability to select those transboundary aquifers (or areas of transboundary aquifers) that require further investigation, directed cross border management and potentially, transboundary agreements governing them.

6.4 Methodology

6.4.1 Study Area

Malawi is a small country in south-eastern Africa and is part of the Southern African Development Community. It is landlocked by Tanzania, Mozambique and Zambia. Groundwater is a vital resource in Malawi, providing 82% of drinking water within rural areas as well as agriculture and industry needs (Chavula, 2012). Malawi has many challenges and limitations for its groundwater supply, particularly within rural areas (Kalin et al., 2019). Threats to aquifers include decreasing groundwater levels, high salinity levels in alluvial deposits, contamination from pit latrine location and -agricultural runoff, an increasing population and the effects of land degradation and climate change on groundwater recharge (Smedley, 2004; Smith-Carrington & Chilton, 1983; Monjerezi et al., 2011a; Bath, 1980; Back et al., 2018; Rivett et al., 2018a; Rivett et al., 2018b; Rivett et al., 2019; Kelly et al., 2019b; Addison et al., 2020).

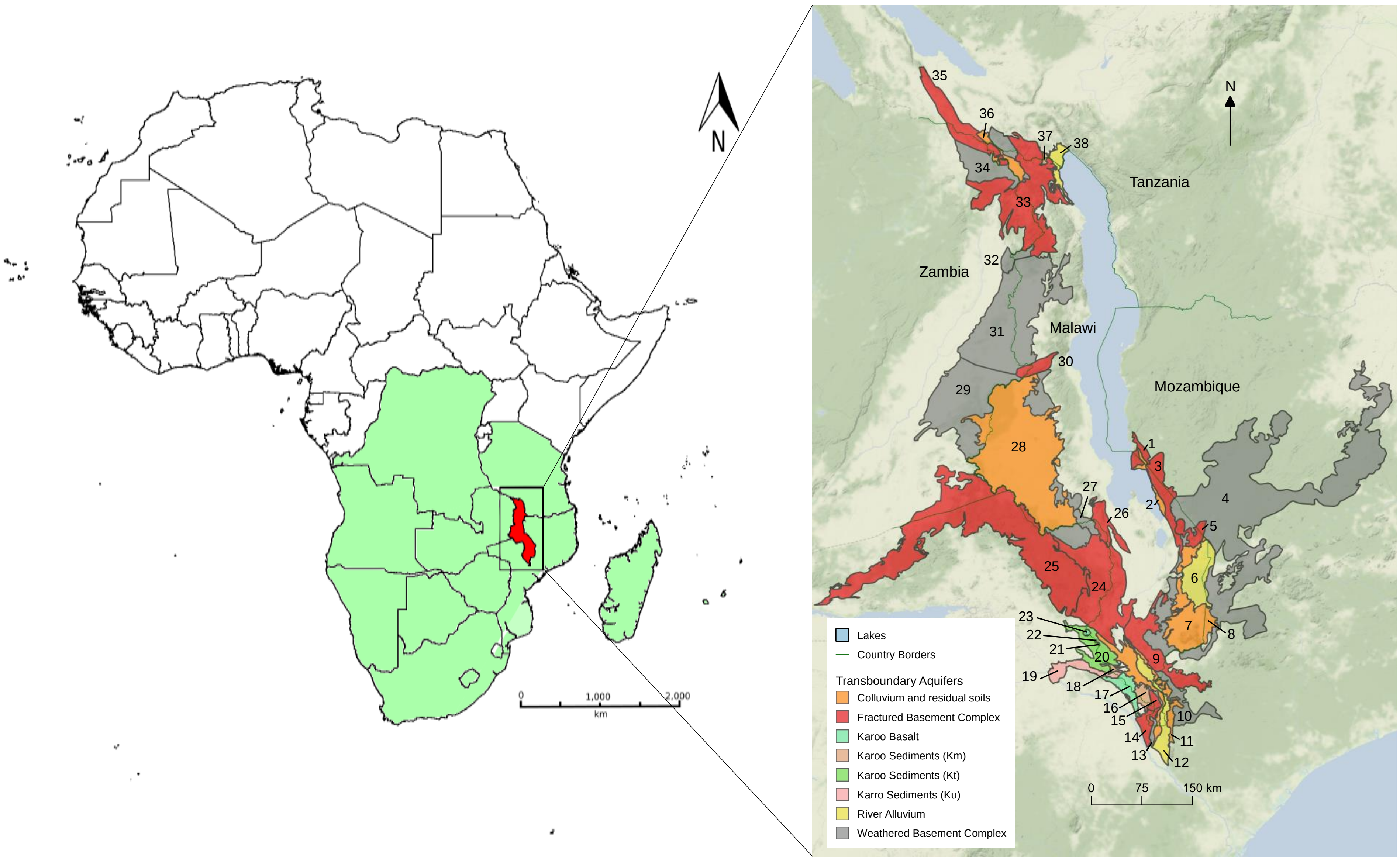


Figure 6.1- Transboundary aquifers shared between Malawi and its neighbours within the wider SADC (Adapted from Fraser et al. 2018, Fraser et al. 2020b)

3 transboundary aquifers in Malawi were first identified by the Global Environment Facility Transboundary Waters Assessment Program' (GEF-TWAP) regional assessments that aimed to provide the first global scale assessment of all transboundary waters (ILEC et al.., 2016; Fraser et al., 2018). More recently, a study by Fraser et al. (2020b) increased this number to 38 by including smaller more locally significant aquifers within their assessment. Figure 6.1 illustrates the current understanding of transboundary aquifers shared between Malawi and its neighbours. Aquifer lithologies include widespread weathered and fractured basement complex, Karoo sediments and basalts, and quaternary alluvium and colluvium. Not all of these transboundary aquifers will be at risk to over abstraction or reduced water quality. Our method, presented in this paper, seeks to identify which of these 38 aquifers, and indeed which areas within these aquifers, pose a potential risk.

6.4.2 Methodological Approach

The method presented here is based on the concept of fuzzy logic first developed by L. A. Zadeh in 1965. It is based on the assumption that people are not thinking in exact variables (yes/no), but distinguish a range of "blurry" values (rather yes, much yes, maybe no, and yes and no). Fuzzy logic can be used as an overlay analysis technique in GIS to solve traditional overlay analysis applications such as site selection and suitability models. The fuzzy logic method assigns membership values to locations that range from 0 to 1. Fuzzy logic site selection is different from other site selection methods because it represents the possibility of an ideal site, rather than a probability. Fuzzy overlay allows the user to overlay the various reclassified layers to analyse the possibility of a specific occurrence. This can then be used to identify a site based on a series of criteria.

Spatial analysis of transboundary aquifers in Malawi was undertaken using fuzzy logic and GIS overlays to generate 'hotspot maps' of areas with the greatest risk of transboundary miss-management. The hotspot map is generated using multiple input raster layers that each have weighted attributes attached to them based on the parameter being modelled, which is then summed to produce a combined raster layer. The higher the cell weight, the worst the case. From this, a heat map is produced highlighting the areas where the highest accumulation of highly weighted categories are shown as "hotspots". Upon generation of the hotspot map, shapefiles of the known transboundary aquifers in Malawi were overlaid and eliminated based on their local or national hotspot significance. Although this method is relatively common practice, it has never been applied to a transboundary aquifer context to assess potential areas of risk due to diminished water quality and quantity, thus giving this approach a novel standing.

The spatial co-location of areas of higher risk for reduced quality and quantity of water that corresponded with transboundary aquifers provides a first indication that the aquifer requires further evaluation. If a hotspot spans across the majority of a transboundary aquifer, the hotspot is deemed to be of a national scale. If the hotspot is only focused along the border, then it is considered to be a local scale hotspot. Hotspots that are out with the limits of transboundary aquifers within Malawi are not considered within this study. Similarly, hotspots that are within a transboundary aquifer but not directly linked to the border are not considered a current transboundary risk.

Three important characteristics should be noted about this method. Firstly, any data or criteria could be used. This means that each user (or country, community etc.) can define what they believe the biggest transboundary risks to be and how they should be weighted. This empowers countries to make their own decisions about their transboundary resources. If arsenic contamination for example is deemed to be an issue, it can be added as a layer. Secondly, the map is data driven but due to its flexibility as described above, a user could select to have only 2 layers or up to as many as needed to define risks. The more data the more accurate the result but even with little available data, results can still be achieved. This makes the method inherently flexible and accessible to data limited countries. Finally, although within a transboundary context, this method has only been applied to one country rather than 2 or more. This was chosen to illustrate that previous transboundary cooperation is not necessary for countries to start to look at their own transboundary circumstances; upon completion of the hotspot analysis, a country could then approach its neighbours with a mandate for future cooperation.

6.4.3 Data Collection

The case study and the chosen area should dictate what data is used for the creation of the hotspot maps. The selected data layers for this study were agreed upon through consultation with the Government of Malawi's Ministry of Agriculture, Irrigation and Water Development Department, based on groundwater quality and quantity concerns. Malawi, like most of Southeast Africa, had limited data for certain parameters on which to base groundwater assessments on (Adelana and MacDonald, 2008). Instead, we used proxies for these parameters which we believe to be suitable substitutes.

The primary data source for this assessment is the Climate Justice Fund: Water Futures Programme (CJF) asset management dataset that is hosted on the mWater platform (www.mwater.co) Data were collected through a series of water point functionality and household level surveys using a method often termed as 'water point mapping'. Information gathered included waterpoint functionality, geographical location, accessibility, reliability and communities served. In total, 120,935 water points, 278,045 sanitation points and 10,297 waste sites were assessed with 5 pieces of site data per water point collected, 81 questions per Water Point Functionality Survey asked and up to 23 questions per Sanitation Survey asked. 93,000 water and sanitation points were used for this study with data from 4 of the specific questions asked used. These were supplemented by 2 open source shape-files of hydrology and land use (Persits, 2002; Upton et al., 2018; MASDAP, 2019)

6.4.4 Data Selection and Weighting

This hotspot spatial analysis was undertaken using 6 combined raster files. Each data point within these 6 files were given a weighting between 0 and 1 based on a selected criterion. The higher the weight, the worse the case and thus the higher the risk rating. Table 6.1 summarises the parameters selected for this case study and the weight selected for each attribute.

Layer 1 is water point type. Water point type data were collected during the CJF water point functionality survey through observation. Water point type is used here as a proxy for water supply reliability. Attributes within the water point layer are (1) hand dug wells, that are considered to have the lowest water supply reliability and thus given a weighting of 1 indicating a high level of risk, (2) mechanically drilled boreholes, that are considered more reliable that a hand dug well and given a rating of 0.5 (MacDonald et al., 2019), and finally (3) piped water supply, that is considered to have the highest level of reliability in this scenario is given a weighting of 0 indicating low risk.

Layer 2 is the hydrogeology of the aquifer. This consists of open source shapefile data obtained from the BGS (Upton et al., 2018). Hydrogeology is used as a proxy water supply availability as some aquifer types provide better yields of water than others (Upton et al., 2018). Attributes within the hydrogeology layer are (1) Basement lithology, considered to have the lowest availability due to low yields and thus given a weighting of 1 indicating a high level of risk, (2) Karoo sediments and basalts, that produce higher yields than basement lithologies and hence given a weighting of 0.5, and finally (3) Alluvial and Colluvium lithologies that provide the highest yields and therefore given a weighting of 0 indicating low risk (Smith-Carrington and Chilton, 1983).

Layer 3 is number of users per water point. The data were collected during the CJF water point functionality survey through questioning of a local community representative. This layer is used as a proxy for stress on the aquifers water supply. When a water point exceeds the number of recommended users, this can cause stress on the aquifer. There are two attributes within layer 3, (1) when the number of users is above Government of Malawi guidelines of 250 users per borehole and 120 per tap (Stoupy and Sugden, 2003) then a weighting of 1 is given and (2) when the number of users is at or below these guidelines, a weighting of 0 is given.

Layer 4 is proximity to pit latrine. Pit latrine and water point GPS location data were collected during the CJF water point functionality survey through observation. GIS was then used to represent the data spatially and determine the distances between water points and pit latrine. Drinking water sources that are close to pit latrine locations are more susceptible to faecal contamination and thus proximity to pit latrine is a proxy for water quality (Back et al., 2018). The Government of Malawi guideline for pit latrine location is that it should not be situated within 30 meters of a water point (MoIWD, 2008). Attribute (1) within the layer are water points within 30 meters of a pit latrine and are given a weighting of 1 indicating the highest risk. Attribute (2) within the later are water points out with 30 meters of a pit latrine and are given a weighting of 0.

Layer 5 is land use. This consists of open source shapefile data obtained from Malawi's Spatial Data Platform (MASDAP, 2019). Different uses of land can cause a variety of pressures on groundwater. Here, we use land use as a proxy for potential nitrate contamination as heavy industry and agricultural land use can contribute to elevated concentrations of nitrate being released into the environment (Wongsanit et al., 2015; Lapworth et al., 2017; Wick et al., 2012). Attribute (1) within the layer represents areas of settlement/cropland and industry and are given a weighting of 1 indicating a high risk of nitrate contamination. Attribute (2) represents forest/grasslands/wetlands where nitrate contamination risk is considered low and are thus is given a weighting of 0.

Finally, layer 6 is seasonal fluctuation. These data were collected during the CJF water point functionality survey through questioning of a local community representative. Groundwater levels in Malawi fluctuate due to seasonal recharge and baseflow impacts (Kelly et al., 2019b). At times, groundwater levels can drop below borehole and shallow dug well depths. Seasonal fluctuation of available water from a water point is used as a proxy for groundwater reliability. A source that is seasonally fluctuating is considered less reliable than a source that supplies water all year round.

Attribute (1) represents all water points that are seasonally fluctuating and thus are given a weighting of 1. Attribute (2) represents a source that is not seasonally fluctuating and is given a weighting of 0. Once combined, the cumulative weighting of each data point was calculated and was given within a range of 0 to 6. This overall weighting was then presented spatially in GIS.

Table 6.1 - Input layers for hotspot map

Layer	Attribute	Weight	Data type/Location
Water point type	(1) Hand dug well	1	mWater point data
	(2) Hand pump/borehole	0.5	
	(3) Piped supply	0	
Hydrogeology type	(1) Basement	1	GIS Shapefile
	(2) Karoo	0.5	
	(3) Alluvial/colluvium	0	
No of users per water point	(1) Above Gov. of Malawi guidelines (> 250/BH, 120/tap)	1	mWater point data
	(2) At or below Gov. of Malawi guidelines (< 250/BH, 120/tap)	0	
Proximity to pit latrine	(1) Out with guidelines (<30 meters)	1	mWater point data
	(2) Within Malawi guidelines (>30 meters)	0	
Land Use	(1) Settlement/Cropland/Industry	1	GIS Shapefile
	(2) Forrest/Grasslands/Wetlands	0	
Seasonal fluctuations	(1) Yes	1	mWater point data
	(2) No	0	
No data		0.5	

6.4.5 Existing Methodologies

Methods to prioritise transboundary aquifers for directed management already exist. Davies et al., (2013) sought to identify transboundary aquifers in most need within the Southern African Development Community. The method employed aimed to classify 14 transboundary aquifers within the region based on how 'troublesome' they are. Criteria used included groundwater flow and vulnerability/susceptibility, groundwater knowledge and understanding, governance capability, socio-economic/water-demand capability and environmental issues. Results indicated that only 2 of the 14 aquifers assessed were considered to be troublesome. Curiously, neither of these two aquifers have been party to any further study. Instead, 3 of the remaining 12 aquifers have had projects dedicated to the assessment and management of them. These are the Shire Valley Alluvial Aquifer through the Shire CONWAT project, the South West Kalahari/Karoo Basin Aquifer through the GGRETA project and the Zeerust-Ramotswa-Lobatse Dolomite Basin Aquifer through the Ramotswa Project (SADC-GMI, 2018; IWMI, 2019; UNESCO-IHP, 2016). This method is limited by its applicability to only entire transboundary aquifers. Often, large parts of transboundary aquifers are not utilised, especially those that expand across large areas, or, parts are not at risk due to the low population rates residing within them (Fraser et al., 2018). This method also risks misrepresenting parts of transboundary aquifers based on data from potentially only one area.

The term ‘transboundariness’ has been coined by Sanchez et al. (2018a) to describe a method that identifies and prioritises transboundary aquifers based on a political and socio-economic criterion. Data used includes population metrics, water quality, data/research availability, political recognition as transboundary, cooperation efforts and other issues governing the agenda. The approach is applied to the Texas-Mexico case study, where transboundary aquifers are fairly well understood and often recognised constitutionally (Sanchez et al., 2016; Sanchez and Eckstein, 2017; Sanchez et al., 2018b). Results split the aquifers into priority groups based on their “transboundariness”. The more ‘transboundary’ an aquifer is considered, the higher the priority it is given. The term ‘priority’ refers to the level to the level of attention or importance given to an aquifer. Thus, the approach considers those aquifers with the most attention and data availability to date as the highest priority. The approach does not prioritise TBAs based on need but rather highlights those which have been given priority up until now (Sanchez et al., 2018b). Although affective to identify which aquifers are currently receiving the most attention, this method does not allow the user to identify which transboundary aquifers may be at risk of any contamination or reduction in water quantity in the future. Furthermore, within the context of countries where transboundary aquifers are not as well studied, understood or recognised, this method is not applicable.

Finally, Sanchez et al. (2020) developed an approach to identify the priority areas within a single aquifer using pumping well location and density as an indicator. Areas identified as having a high density of wells are termed “effective transboundary aquifer areas”. These areas can be considered priority zones by both local and national governments for more specific and specialised transboundary management between riparian states. By focusing only on aquifer abstraction, this method negates the importance of water quality within transboundary aquifers and thus makes it unsuitable for areas where transboundary aquifers are at risk of reduced water quality, like the Malawi case study.

Our method seeks to highlight the importance of both water quantity and quality within the SADC transboundary aquifer context where financial resources and groundwater data are often limited. Water point mapping is common practice within the region and by utilizing this data for an alternative use, we can fill the gap left by a lack of comprehensive aquifer studies within the region. Furthermore, through the established approach, we can single out individual problematic water points for single case rehabilitation.

6.5 Results and Discussion

6.5.1 Hotspot Analysis

Figure 6.2 shows results of the hotspot analysis. Darker areas indicate a higher risk to groundwater than lighter areas. The insert in figure 6.2 illustrates the detail of the risk analysis. Each individual water point (>93,000) has a rating assigned to it. The spread of the higher risk areas can be said to be directly related to population. In the centre and southern regions of the country, population is much higher than in the North. These areas inherently require a greater number of water points for access to groundwater. This however does not mean the northern areas may not be at risk. Multiple areas in the north exhibit smaller but equally at risk water points. Here, pressure from contamination may be more of a driving factor than over abstraction risk.

It is important to highlight that this risk analysis is confined within the international borders of Malawi. In places where hotspots have been indicated along the border in Malawi, it cannot be assumed the situation is the same across the border. However, it provides the Government of Malawi's reasons to responsibly notify a neighbour that they share a transboundary aquifer that has been highlighted as potentially at risk for groundwater contamination or over abstraction. In areas where groundwater flow direction is moving from Malawi to a neighbouring country it can be deemed that the risk for that neighbouring country is just as high as in Malawi. This is because (1) any contamination to the aquifer in Malawi has the potential to travel across the border into a neighbouring country, and (2) over-abstraction to an aquifer in Malawi could lead to a change of groundwater flow patterns to a neighbouring country or even a reversal of groundwater flow. These would cause groundwater quality and quantity issues in a neighbouring country to Malawi.

The hotspot analysis shown in figure 6.2 also highlights areas within Malawi where groundwater is not currently being used. Areas with a lack of water point data indicate that surface waters or a piped supply system is in place, likely from surface reservoirs. This information could be useful to the Malawi Government as these areas could be exploited within the future for increased water availability and thus increased water security. This is especially viable in areas of the country that exhibit high yielding aquifers.

The insert within figure 6.2 covers the Mulanje areas of Malawi that borders Mozambique. At this scale, individual water points can be seen. This can be useful to assist in identifying the exact location of the most 'at risk' water points. Isolating these water points and ensuring they are managed effectively could greatly reduce the risk to the overall aquifer.

Sections 6.5.2 and 6.5.3 will illustrate which of the previously identified 38 transboundary aquifers (figure 6.1) show potential national scale and local scale hotspots of transboundary risk. Transboundary aquifers that do not exhibit any sign of national or local scale hotspots from figure 6.2 are negated from further discussion. Although these transboundary aquifers should continue to be monitored, it is deemed that they do not pose a current transboundary risk.

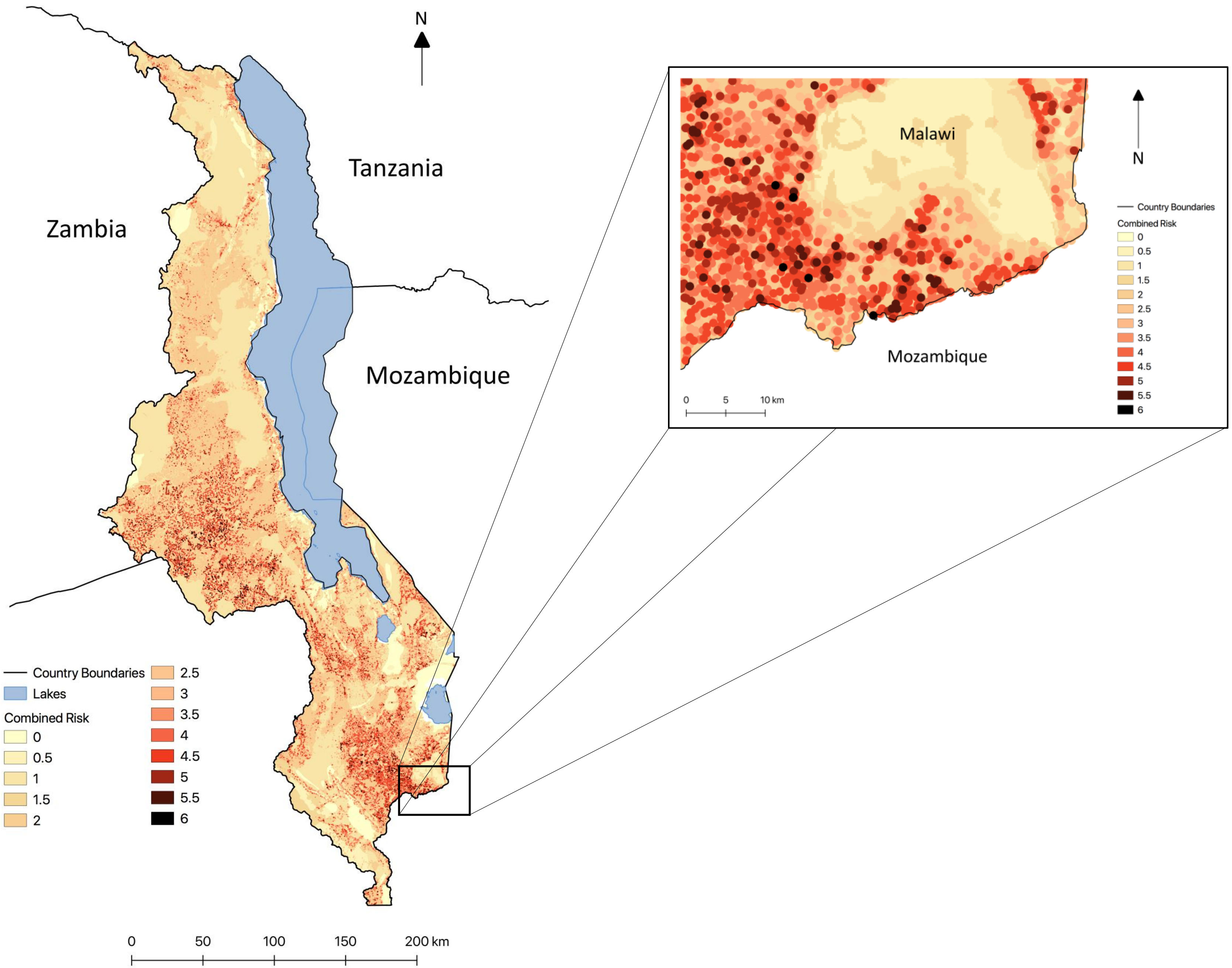


Figure 6.2 - Risk Hotspot Analysis Results

6.5.2 National Scale Hotspots

Figure 6.3 illustrates the generated hotspot map overlaid with selected transboundary aquifers from figure 6.1 that cover identified national scale hotspots; where a hotspot spans across the majority of a transboundary aquifer. In total, there are 3 transboundary aquifers that exhibit a national scale of risk. They range in sizes from the largest being 37313.1 km^2 to the smallest at 3849.2 km^2. Due to the large spread and high density of the water points within these hotspots, they must be considered and dealt with at the national level, not at local level. The national scale hotspots all reside in the central and southern region of Malawi; where the greatest population density is. This emphasises that as population rises, the risk to an aquifers water quality and quantity also increased. The transboundary aquifers aligned with these hotspots are also all of basement complex lithology; highlighting that large populations are relying on low yielding aquifer types in these areas. Descriptions of each national scale aquifer are supplied in Appendix C.

6.5.3 Local Scale Hotspots

Figure 6.4 illustrates the hotspot map overlaid with selected transboundary aquifers that cover identified local scale hotspots; where a hotspot is primarily focused along the border and does not spread further inland into the aquifer. In total, there are 11 transboundary aquifers that exhibit a local scale of risk. Due to the isolated and smaller nature of these hotspots, they can be considered a more local risk and thus managed in such a way.

The local scale hotspots are spread fairly evenly throughout Malawi. They range in sizes from the smallest being 228.5 km^2 to the largest at 8616.7 km^2. The lithology of these aquifers are variable; ranging from basement complex to colluvial and alluvial superficial deposits. The hotspots within these aquifers are all much more isolated than the nationals scale hotspots. There could be multiple reasons for this; (1) these areas tend to be more rural and secluded with no larger populations close to the hotspots, (2) specific issues relation to particular communities could influence

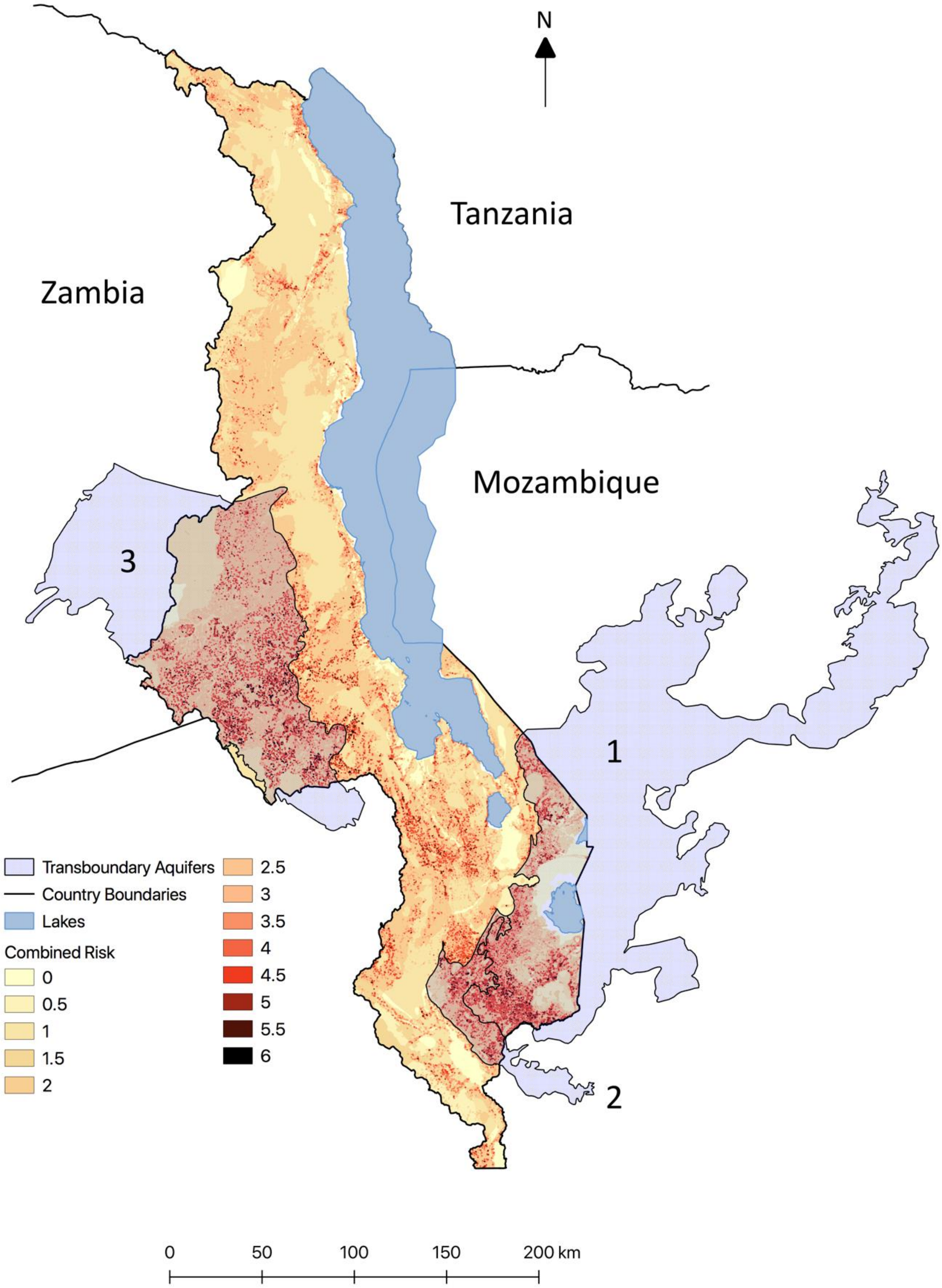


Figure 6.3 - National scale hotspots and correlated transboundary aquifers

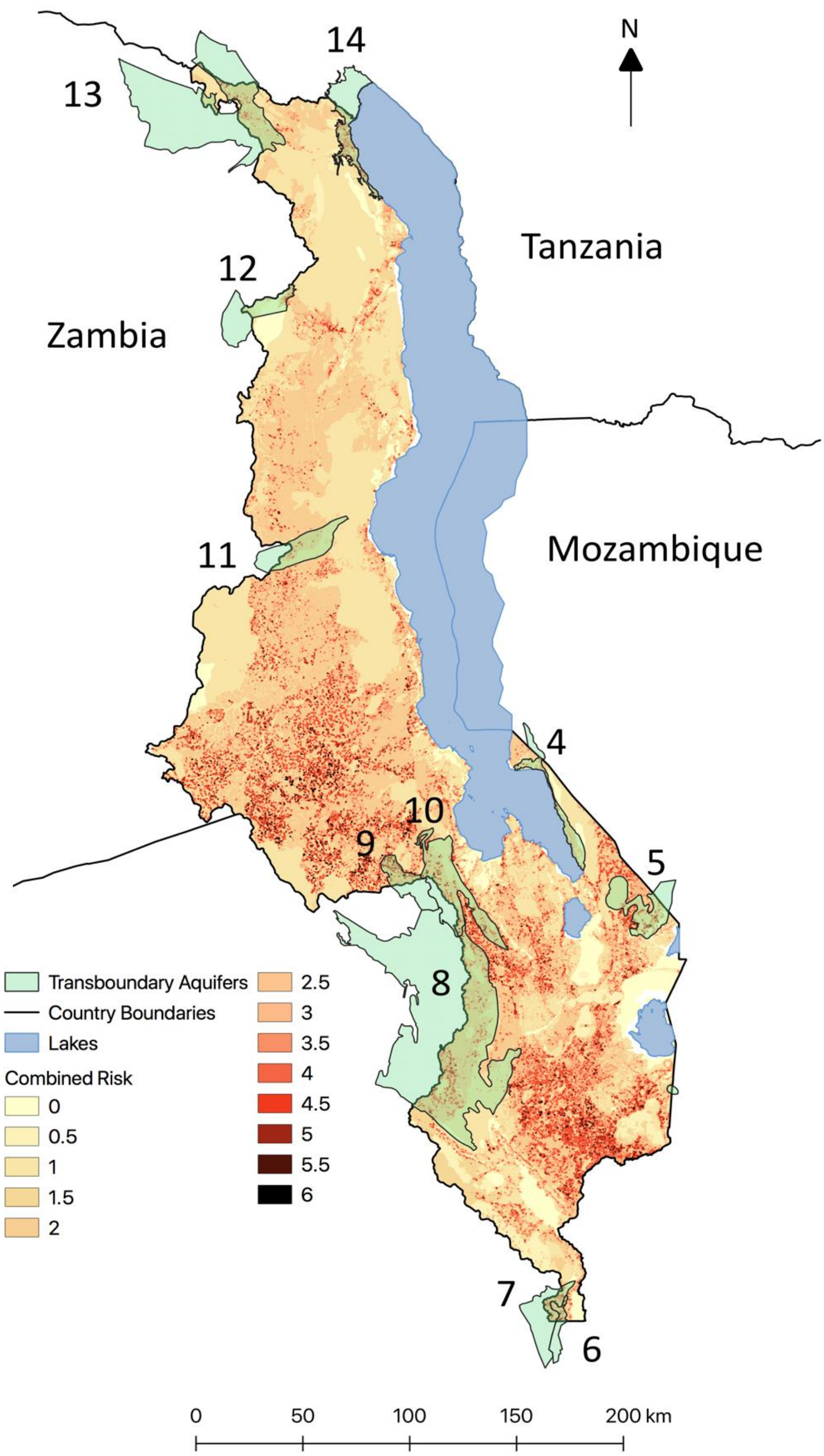


Figure 6.4 - Local Scale hotspots and correlated transboundary aquifers

local scale hotspots such as poor pit latrine location planning, the community being located on a low yielding aquifer, or a specific land use type within the community, such as a focus on agriculture. Descriptions of each national scale aquifer are supplied in Appendix C.

6.5.4 Transboundary Responsibility

Of the 14 aquifers that have been identified as exhibiting at risk hotspots, only 4 of them have a groundwater flow regime that runs from Malawi into a neighbouring country. The other 10 aquifers have groundwater flow that moves into Malawi from a neighbouring country. Groundwater flow direction can influence transboundary impacts and thus management. Aquifers 2, 6, 7 and 14 (see Appendix C) are considered high risk transboundary aquifers that exhibit transboundary flow from Malawi to a neighbouring country. In the case of these aquifers, the Malawi government must recognise that their impacts will affect their downstream neighbours. Ensuring good water quality and sustainable abstraction rates will assist in negating negative impacts to bordering countries. Conversely, it is also in Malawi's best interest to ensure that the other 10 transboundary aquifers, which flow into Malawi from neighbouring countries, are managed sustainably to reduce any potential contaminated groundwater crossing into Malawi's portion of the transboundary aquifer alongside ensuring groundwater levels do not reduce over time.

6.5.5 Multi-Scale Management

No two aquifers are the same, and this assertion is the same for transboundary aquifers (Eckstein, 2012). Lithology, transmissivity, storage capabilities, abstraction rates, populations dependency, seasonal fluctuations are just some factors that may affect how a transboundary aquifer is used. The use of an aquifer should then inform how it is managed (Eckstein, 2012). For example, a small aquifer used by a limited number of users within a highly productive lithology will require a different management strategy to a large aquifer utilised by a large population with a low recharge rate. Classifying what type of management is required of an aquifer is particularly important in countries like Malawi, where resources and financial reserves are limited. Within a transboundary context, it is even more essential to ensure that the selected management type is established in cooperation with neighbouring countries. Available resources should be directed to aquifers in most need for management on a case by case basis, but there are limited methods currently to identify what aquifers within a country like Malawi should get the highest priority. It is difficult to identify what aquifers may require a specific level of management compared to others (e.g. local vs. national), and which aquifers currently aren't at risk for over abstraction or contamination and can be left alone.

National border based assessments (Fraser et at, 2020) generate data that allow Governments evaluate their transboundary aquifers in detail. Hotspot analysis of these identified transboundary aquifers as conducted in this study highlight which aquifers require immediate attention and at what scale. But what management is appropriate for these transboundary aquifers? Figure 6.6 highlights the relationship between the information generated from differing transboundary aquifer assessment types and transboundary management they could inform.

Regional assessments are useful in identifying large transboundary aquifers that may be impacted on a regional scale. For example, the 'Global Environment Facility Transboundary Waters Assessment Program' (GEF-TWAP) regional assessment identified 80 transboundary aquifers across south eastern Africa that are of high importance across the region (ILEC et al., 2016). These aquifers are best managed under inter-governmental organizations like the River Basin Organization 'ZAMCOM' that bring together riparian states to facilitate and promote the sustainable management of water resources within the region due to their large scale and regional (ZAMCOM, 2019).

National border based assessments in comparison can inform international (government to government) and local level (district to district) management (Figure 6.6). Transboundary aquifers in Malawi that have been identified as exhibiting national scale hotspots are good candidates for international management. These aquifers present a significant enough risk at the national level to warrant the Government of Malawi to notify and cooperate with its neighbouring country governments in order to ensure management of these shared aquifers. This is best done through an international transboundary agreement or an international institutional governance mechanism. International agreements over shared groundwater are however still in their infancy; globally, there are only 6 transboundary aquifer agreements governing the use and management of shared groundwater (Rivera and Candela, 2018), only 1% of identified transboundary aquifers worldwide. Each are unique to the aquifer in question. Examples include; the Genevese Aquifer agreement, that governs the management and allocation of water along the French-Swiss border aquifer (de los Cobos, 2018); the Nubian Sandstone and Northwestern Sahara Aquifer agreements that facilitate data sharing between parties (NSAS 2002, SASS 2002 in Eckstein. 2011) and the Al-Sag/Al-Disi agreement that created a protected area of 10 km within either side of the border for the fossil (non-recharging) aquifer (Burchi, 2018) Most recently, the UN Draft Articles on the Law of Transboundary Aquifers were developed to provide guidelines for countries wanting to foster agreements over the management of their transboundary aquifers. They cover all aspects of potential transboundary scenarios including transboundary recharge and fossil aquifers. (UN, 2008; Sanchez et al., 2016). The Draft Articles assisted in development of The Guarani Aquifer Agreement that draws from 4 of the Draft Articles covering equitable and reasonable use, the obligation to cause no harm and the exchange of technical data (Villar and Ribeiro, 2011; Sindico et al., 2018a). A transboundary agreement over any of the identified nationally at risk aquifers within Malawi could build on the lessons learnt from these agreements. There are currently very few institutional mechanisms that act to govern the use and management of transboundary aquifers in replacement of a formal agreement at the international and binational level, particularly within the African context (Fraser et al., 2020b). Moving forward, Malawi could look to set up a binational commission to govern the use and management of the 4 national scale transboundary hotspots identified however this would require a strong mandate and willingness to cooperate from all involved stakeholders, which can take time to develop.

Transboundary aquifers in Malawi that have been identified as exhibiting only local scale hotspots are likely too small to justify a full cross border international agreement or to justify binational commissions forming to govern them. These issues could be addressed at the local scale particularly because Malawi's water regulations are decentralised to the district level (Truslove et al., 2020). This approach has been carried out successfully in multiple other countries including the Hueco Bolson Aquifer underlying the cities of El Paso and Juárez on the Mexico–United States border (Juárez–El Paso MoU, 1999 in Eckstein, 2011), the Abbotsford–Sumas Aquifer between the US State of Washington and Canadian province of British Columbia, and the 1999 Memorandum of Understanding between the Municipal Water and Sanitation Board of the City of Juarez (in Chihuahua, Mexico) (Abbotsford–Sumas MoA 1996 in Eckstein, 2011; Eckstein, 2012). Local scale management has also been suggested as an alternative to fostering formal agreements along the border between USA and Mexico (Eckstein, 2012). A local agreement could be informal or in the form of a memorandum of understanding, but there is nothing to stop parties creating an official agreement on a smaller scale.

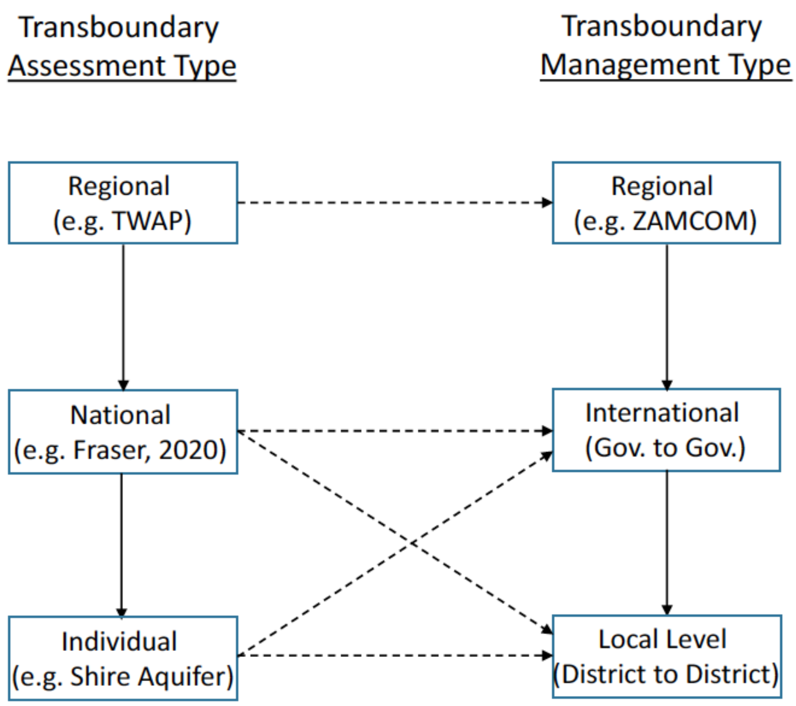


Figure 6.5 - Flow diagram illustrating the relationship between different transboundary aquifer assessments and management types

Local scale management can be advantageous for multiple reasons. Local communities often have the biggest stake in good transboundary management; small changes to a local aquifer can have large impacts on reliant communities. Communities are often best informed about issues within the area. Local communities along the border region are also more likely to have links to individuals, communities or businesses on the other side of the border (Eckstein, 2012). In Malawi for example, many communities close to the border speak the same language and practice the same religion as their cross-border counterparts due to pre-colonialism tribal connections (Kaspin, 1997).

There is already evidence of local scale transboundary cooperation in Malawi. The district of Mulanje, situated on the southeast border of Malawi are party to semi-regularly meetings with neighbouring district, Milange, In Mozambique. Representatives from the two districts meet and discuss shared issues such as trade, border control and management of their shared river, the Ruo, that runs along the border between the two districts. One could make a case for the addition of transboundary groundwater to be added to this working groups mandate. An informal local agreement over the use and management of transboundary aquifers in Malawi might include clauses for regular exchange of data, joint monitoring of boreholes, the inclusion of local stakeholders such as communities and local businesses.

6.6 Conclusions and Recommendations

The approach used in this study identified transboundary aquifers in Malawi that are at risk to over abstraction or reduced water quality (hotspots). The use of fuzzy logic and GIS overlay pinpointed specific areas within a country that may be at transboundary risk. The method provides the Malawi government with a tool to prioritise which transboundary aquifer require management and international agreements. In the Malawi case study where water management is decentralised, it also gives the opportunity for the identification of areas where local scale transboundary management can play an important role in managing cross-border water resources.

Results of this study can inform the Malawi Government where to direct available resources for transboundary groundwater management. There are 3 transboundary aquifers highlighted in this paper thought to be at high risk of over abstraction and contamination and which require consideration for transboundary agreements. There are a further 11 hotspots on smaller scale transboundary aquifers that could be managed at the local level. A ‘transboundary diagnostic analysis’ and coherent conceptualization of these transboundary aquifers could assist in greater understanding of what management practices are needed. This should ideally be done in cooperation with neighbouring local stakeholders and governments.

6.7 Postface

This chapter answered RQ3 ‘Do all transboundary aquifers require detailed assessments, management and agreements governing them?’ A methodology was presented for identifying hotspots within transboundary aquifers may be vulnerable to the groundwater quality and quantity issues (SO7). This method was applied to the Malawi case study where we identify which of Malawi’s transboundary aquifers should be prioritised for directed national and local level management based on vulnerability hotspot mapping. Results indicated that there are 11 local scale and 3 national scale hotspots of transboundary concern within Malawi (SO8). Engaging these stakeholders and building capacity in these areas will be essential for multi-scale management. Finally, a discussion of the importance of multi-scale management approaches to transboundary aquifers is given, highlighting ways in which institutional organizations and transboundary agreements and arrangements can assist in its implementation (SO9).

The next chapter will explore what role geochemical and isotopic analysis might play in assessing the transboundary nature of an aquifer and as a tool for management decisions. It utilises the Mulanje hotspot as a case study as identified in chapter 6.

7 An Isotopic and Geochemical Assessment of the Ruo Transboundary Aquifer System to Inform Sustainable Management, Malawi-Mozambique[4]

7.1 Preface

The previous chapter (chapter 6) presented a methodology for identifying hotspots within transboundary aquifers that may be vulnerable to the groundwater quality and quantity issues, and applied it as a Malawi case study. One such hotspot identified was in multi-scale transboundary aquifer that partly resides in the Mulanje District of Malawi. The aquifer is a two layered system composed a weathered basement lithology overlaid by unconsolidated colluvium.

This final research chapter explores what role geochemical and isotopic analysis might play in assessing the transboundary nature of an aquifer (RQ4). It utilises the Mulanje hotspot as a case study. A month long field campaign was conducted in the Mulanje District of Malawi and the neighbouring Milange District in Mozambique to collect water samples from surface and groundwater sites. 36 samples were collected and analysed for isotope and geochemical parameters (SO10). An interpretation of the results of the analysis highlight that the river that runs through the field area is fed by transboundary groundwater and that there is indeed transboundary groundwater flow across the border that flows from Malawi into Mozambique. A conceptual model of the transboundary water interactions was developed (SO11). Finally, a discussion of appropriate management of the transboundary aquifer is presented. It is recommended that management of this transboundary system is undertaken at the local scale ensuring regular monitoring of groundwater and surface waters and cross border exchange of data.

This chapter is a submitted paper within Hydrogeology Journal.

Paper reference:

[4]Fraser, C.M., Banda, L.C.., Kalin, R.M. 2020. An Isotopic and Geochemical Assessment of the Ruo Transboundary Aquifer System, Malawi-Mozambique. Hydrogeology. Submitted.

Author contribution:

Conceptualization (C.M.F, R.M.K), field work (C.M.F., L.C.B), data curation (C.M.F, L.C.B), laboratory analysis (L.C.B), investigation (C.M.F), methodology (C.M.F., L.C.B.), validation (C.M.F., M.K., Z.U.), Interpretation (C.M.F), visualization (C.M.F.), project administration (R.M.K), supervision (R.M.K), writing original draft (C.M.F), review and editing (C.M.F., R.M.K.., L.C.B.)

It should be highlighted that section 7.4.2 of the methodology within the paper was written by the co-author Limbikani Banda.

7.2 Abstract

Transboundary groundwater provides essential water supplies for many people worldwide. It is therefore essential to understand how transboundary systems operate including where they are recharged from, how surface water and groundwater interact and most importantly, how and where transboundary groundwater crosses international borders. To date, the scientific understanding of transboundary aquifers had been limited in comparison to shared surface waters. Isotopic and geochemical analysis can shed light on important groundwater interactions and assist in the conceptualisation and management of transboundary aquifer systems. We used isotope and geochemical analysis to assess a 'transboundary aquifer hotspot' between Malawi and Mozambique that is suspected to be under pressure from over-abstraction and subject to reduced water quality. Thirty-six water samples from boreholes, shallow wells and rivers were collected from the adjoining Mulanje and Milange districts in Malawi and Mozambique, respectively. Interpretation of results indicated that: (1) the Ruo River that forms the border between Malawi and Mozambique is fed by groundwater from a shallow colluvium aquifer on the Malawi side; (2) deep groundwater from a weathered basement aquifer moves across the border from Malawi into Mozambique; (3) there is mixing between two aquifers in the field area; and (4) recharge to the system comes from precipitation on both sides of the border. A conceptual model was developed, depicting these results in an accessible format. These results have implications for management of the transboundary system. With the limited likelihood of a government-to-government transboundary agreement being established for this aquifer system in the near future, it is recommended that management of this transboundary system is undertaken at the local scale ensuring regular monitoring of groundwater and surface waters and exchange of data.

Key Words

Stable Isotopes, Geochemistry, Groundwater, Transboundary, Africa, Malawi, Mozambique

7.3 Introduction

Water security drives economic development, health, and welfare (Grey and Sadoff, 2007; Hunter *et al.,* 2010). Groundwater provides over 97% of available water resources across the world (IGRAC and UNESCO, 2015a). In many countries, groundwater is the only reliable resource for safe water supplies and food security (MacDonald and Calow, 2009). Groundwater systems respond more slowly to meteorological conditions than surface water, and as such, provide a natural buffer against climate variability, including drought (Calow *et al.,* 1997, 2010). Groundwater generally does not require treatment (MacDonald *et al.*, 2012). Increased pressure on these resources from rapid population growth may compromise water security. This issue is particularly prominent in Africa, where up to 75% of the population on the continent relies on groundwater as their main source of drinking water (UNECA *et al*., 2000), and access to groundwater is essential across the continent for rural livelihoods such as livestock rearing and agricultural crop cultivation (Villholth, 2013 and Foster *et al.*, 2008 in Nisanje et al., 2018). The population in sub-Saharan Africa is projected to double by 2050 (United Nations, 2019). To develop secure water supplies, the quantity, quality and sustainability of groundwater resources must be known (MacDonald and Calow, 2007). However, there is still very little information at national scales to inform national planning and sustainable development of groundwater resources. Information on groundwater quality is particularly scarce across Africa, and vital for sustainable management and appropriate development of the resource to improve water security across the continent (Foster and Chilton, 2003; MacDonald *et al.,* 2012).

Water is not bound by political boundaries and can cross international borders travelling from one sovereign country or state into another (Wada and Heinrich, 2013). This is termed ‘transboundary’ water movement. Rivers, lakes and groundwater often are transboundary; 40% of water worldwide that we depend upon is estimated to be transboundary (Eckstein, 2017). Internationally, transboundary surface waters are better understood in comparison to their less visible groundwater counterpart (Eckstein and Sindico, 2014). Transboundary aquifers are less studied and have fewer legal agreements governing their use and management (Rivera and Candela, 2018). A current challenge faced by many countries is to accurately define the movement of groundwater through transboundary aquifers and translate this knowledge into management policies (Fraser *et al.*, 2018). This challenge is compounded by the Sustainable Development Goals (SDG) adopted by the UN in 2015 that specifically asks for the implementation of integrated water resource management of water resources, at a transboundary level (SDG 6.5.2) where appropriate (Mccracken, 2017).

Recent research has called for countries to take ownership of their transboundary responsibilities (Fraser *et al.*, 2020c). This should include conducting a detailed and national-border based approach to transboundary aquifer assessments and then identifying which of their transboundary aquifers may pose a transboundary risk in terms of reduced quality and over-abstraction of groundwater (Fraser *et al.*, 2018; Fraser *et al.*, 2020b; Fraser *et al.*, 2020c). A comprehensive understanding of the groundwater dynamics of a transboundary aquifer system is vital for any successful transboundary cooperation policy (Al-Gamal, 2011). Upon completion of a national border based assessment, a study in Malawi concluded there are 38 transboundary aquifer units shared between Malawi and its neighbours in contrast to a previous estimate of 3 (Fraser *et al.*, 2018; Fraser *et al.*, 2020b). Further research aimed to identify hotspots within transboundary aquifers in Malawi where groundwater may be vulnerable to quality and quantity issues, resulting in 11 local scale and 3 national scale hotspots of transboundary concern (Fraser *et al.*, 2020c). These require further assessment and attention to ensure their sustainable management. The aim of this study was to investigate one of these hotspots in greater depth to understand the transboundary relationships of water movement, and to develop a management strategy appropriate for the transboundary circumstances present.

Isotope and geochemical analysis has long been used to increase understanding of water systems (Kalin and Long, 1994). Isotope and geochemical analysis can establish groundwater age and/or provenance, enhance understanding of flow regimes, elucidate surface water-groundwater interactions, identify seasonal influences on surface water, indicate system stress, source contamination issues, highlight chemical composition and water quality, and support the understanding of recharge mechanisms (Kalin, 1996; Kalin, 2000; Hameda *et al.*, 2012; Bath, 1980; Srinivasamoorthy *et al.*, 2011; Zaporozec 1972; Stumm and Morgan, 1996; Hem, 1991; Drever, 1988; Domenico and Schwartz, 1998; Balagizi *et al.*., 2018; Kotchoni *et al.*., 2018; Resende *et al.*., 2018; Abdalla *et al.*., 2008; Babaye *et al.*., 2018; Faye *et al.*., 2019; (Edmunds, 2009; Fontes *et al.*., 1991; Akpataku *et al.*., 2019; Walker *et al.*., 2019; Bahir *et al.*., 2018; Durowoju *et al.*., 2019; Kebede *et al.*., 2017; Owor *et al.*., 2011; Fontes *et al.*., 1991; Kotchoni *et al.*., 2019; Nivet *et al.*., 2018; Geris *et al.*., 2018; Guendouz *et al.*., 2006; Tarki *et al.*., 2016; Ganyaglo *et al.*., 2017; Re *et al.*., 2011). Isotopic and geochemical analysis has also been used, although not as widely, in transboundary water investigations (Al-Gamal, 2011; Eftimi, no date; Wassenaar *et al.*, 2006; Vystavna, 2018; Zamora, 2018; Abdalla *et al.*, 2018; Normatov *et al.*, 2017; Gao *et al.*, 2011; Ngatcha *et al.*, no date; Szocs *et al.*, 2013).

Isotopes and geochemical analysis is starting to become an established practice in Malawi thanks to the establishment of an isotope hydrology laboratory (supported by the International Atomic Energy Agency) alongside research and financial support from the Scottish Government through the Climate Justice: Water Futures Programme (Monjerezi *et al.*, 2011a; Monjerezi *et al.*, 2011b; Wanda *et al.*, 2011; Banda *et al.*, 2019; Banda *et al.*, 2020; Kambuku *et al.*., 2018a, b; Missi, 2018; Bath, 1980; Chavula, 1995; Monjerezi *et al.*., 2012; Rivett *et al.*, 2018a; Rivett *et al.*, 2018b). In countries like Malawi, where financial resources are limited, and fieldwork is often challenging, isotope and geochemical studies can provide a low cost and simple method of understanding water systems in comparison to time-intensive drilling and pumping tests.

The selected hotspot for this study is part of the Ruo Transboundary Aquifer System situated within the Shire River Basin shared between Malawi and Mozambique. Samples were collected from rivers, shallow wells and boreholes on both sides of the border within the field area and analysed for stable isotopes, major dissolved ions and physiochemical properties. Potential transboundary issues within the selected area include decreasing groundwater levels, salinity issues, contamination of groundwater, increasing population/demand on groundwater and reduced recharge to aquifers. There is, however, no scientific data to support the conceptual assumption that groundwater flows across the international border shared between the two countries. This limits the management of the resource and sustainable use of the aquifer. It is proposed that stable isotope and geochemical analysis will validate transboundary groundwater flow and assist in the conceptual understanding of the system, including recharge zones, groundwater-surface water interaction and transboundary flow. Equipped with this information, both countries can explore means to cooperatively manage the aquifer and ensure its sustainable development. This paper aims to:

- Present the results of a geochemical interpretation for the field area
- Present the results of an isotopic interpretation for the field area
- Develop a conceptual model to illustrate transboundary interactions within the field
- Present a way forward for how Malawi and Mozambique can cooperate over management of the Ruo Transboundary Aquifer System.

7.4 Methodology

7.4.1 Study Area

The study area is a section of the Ruo Transboundary Aquifer System shared between Malawi and Mozambique identified as potentially problematic in terms of water quality and quantity (Fraser *et al.*, 2020c). Malawi and Mozambique are two countries located in the Southern African Development Community. Malawi is landlocked surrounded by Mozambique, Tanzania and Zambia. Mozambique is a large coastal country that sits next to the Indian Ocean but also shares continental borders with Malawi, Zambia, Zimbabwe, South Africa and Eswatini. The aquifer system resides in the south-east of Malawi and the centre of Mozambique, where the two countries borders meet (Figure 7.1). The field area resides within the Mulanje District of Malawi and the Milange District of Mozambique. Previous research suggested that water points within this area are at risk of E. coli contamination from pit latrine placement, nitrate contamination from agricultural runoff and over-abstraction (Fraser *et al.*, 2020c)

The topography of the area can be divided into two distinct regions: The Mulanje Massif, a mountainous area within Malawi to the north of the study area that reaches an elevation of 3002 meters (2200 meters above sea level), formed of a granite igneous intrusion; and the valley plains and savannah leading away from the Mulanje Massif that are between 500 and 800 meters above sea level (Floodmap, 2020). The geology of the field area is dominated by Precambrian crystalline basement rocks formed of gneiss and granulite (UN 1989). The basement complex is intruded by dykes and other igneous lithologies. (UN 1989). Lying on top of the basement lithologies, colluvium dominates. These superficial deposits of residual soils are commonly thin but quite extensive.

There are three main seasons that affect the field area. The “hot wet” season extends from November to March and two dry seasons divided into “cool dry” extending from May to August, followed by a “hot dry” season with progressively increasing temperatures and humidity from September to November (UNDP, 1986; Smith-Carrington and Chilton, 1983). Malawi sits within the equatorial low-pressure area, where the north-east trade wind of the Northern Hemisphere converge with the south-east trades of the Southern Hemisphere. This area is known as the Inter-Tropical Convergence Zone (ITCZ) (Mapona and Xie, 2014). Average daily temperatures range from 24^{o}C to 30 ^{o}C during the dry season (worldweatherlonline 2020). The plateau level at around 2,000 metres above sea level averages more than 2500 mm of rain, however, in the low plains around the foot of the Mulanje Massif within Malawi, the annual rainfall is 1600mm on western slopes of the Massif. Average rainfall in the savannah plains on the Mozambique side is unrecorded. In the plains around the Massif, it normally only rains in the rainy season, while it rains year-round on the plateau (Haarstad *et al*, 2009).

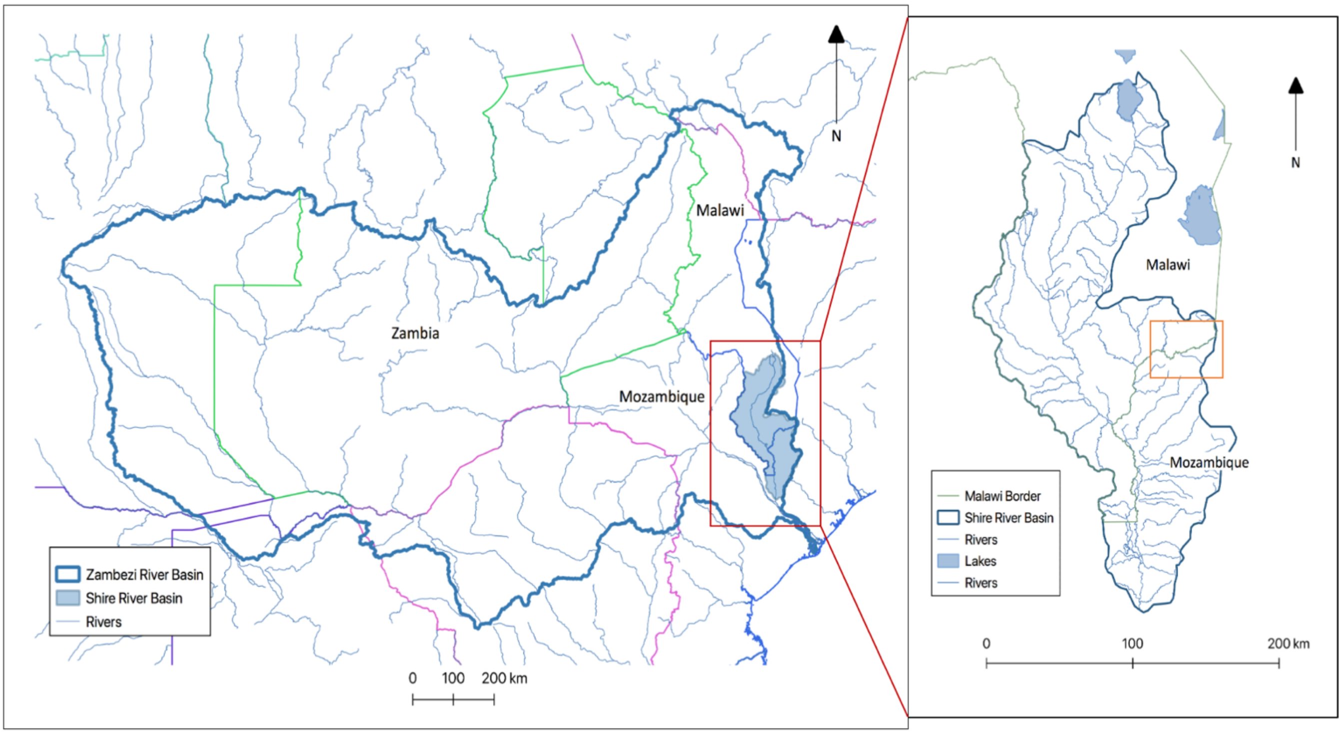


Figure 7.1 – Location of the Shire River Basin within the wider Zambezi River Basin highlighting field area (orange box)

The Ruo River forms the international border between Malawi and Mozambique. The river is the biggest tributary to the larger Shire River that is fed by Lake Malawi (referred to as Lake Nyasa in Mozambique) and forms part of the Shire River Basin. The Shire River Basin is part of the larger Zambezi River Basin, and the Shire River merges into the Zambezi River further south in Mozambique (Figure 7.1). The Shire River catchment is 18,000 km^2 in area and consists of the upper, middle and lower sections, and its average outflow is 395 m^3 s^{-1} (Kululanga and Chavula, 1993; Chavula, 2012). The Zambezi River basin catchment is 1,390,000 km^2 in area (Hamududu and Killingtveit, 2016). Annual discharge of river water to the Mozambique Channel where the River Shire meets the Zambezi River is estimated at some 106 km^3 and accounts for around 85% of the total national river volume discharged (UN, 1989; Ginn, T. 2002; FAO, no date). The Ruo drains a catchment area of nearly 5,200km^2 including most of the watersheds of the Mulanje Massif and the eastern slopes of the Shire Highlands south of Limbe, it enters the Shire from the east at Chiromo. On the Mulanje Massif the annual rainfall reaches up to 3.3 meters, and heavy rain on the mountain produces sudden spates in the rivers that drain the mountains, which in turn play a major part in the flooding in the Lower Shire (Cochrane, 1957).

A large majority of the drinking water within the field area is supplied by boreholes and hand-dug wells (Kalin *et al.* 2019). Two main aquifers exist from which groundwater is supplied: a weathered basement aquifer, and an unconsolidated colluvium aquifer (Figure 7.2). These aquifers are transboundary and potentially hydraulically connected. The system is composed of charnockitic gneiss and granulite lithology overlaid by unconsolidated colluvium. The bottom layer is a weathered basement aquifer that stores and most likely transmits the transboundary movement of groundwater through secondary saprolitic porosity, formed by the hydrolysis of bedrock material by infiltration rainfall which causes mineral leaching, breaking down bedrock in a process known as saporilization (Chilton and Smith-Carrington, 1984; Smith-Carrington and Chilton, 1983 in Fraser et al., 2020b). This basement aquifer has low borehole yields, a transmissivity of between 5-35 m^2/day and hydraulic conductivity of 0.5 - 1.5 m/d.

Groundwater within this aquifer is inferred to be flowing from Mozambique into Malawi in its northern extent, and from Malawi to Mozambique in its southern extent. This basement aquifer is overlaid by another superficial aquifer unit composed of colluvium and residual soils. It is likely that these two aquifers are hydraulically connected. The superficial aquifer is highly productive, with a transmissivity of 50-300 m^2/day and hydraulic conductivity of 1-10m/d (Smith-Carington and Chilton, 1983; Habgood, 1964; Bradford, 1973 in Fraser *et al.*, 2018). Within the field area, the weathered basement aquifer crosses the international border between Malawi and Mozambique. The colluvium aquifer does not cross the border in the field area but is transboundary in other areas of the country (see figure 7.2).

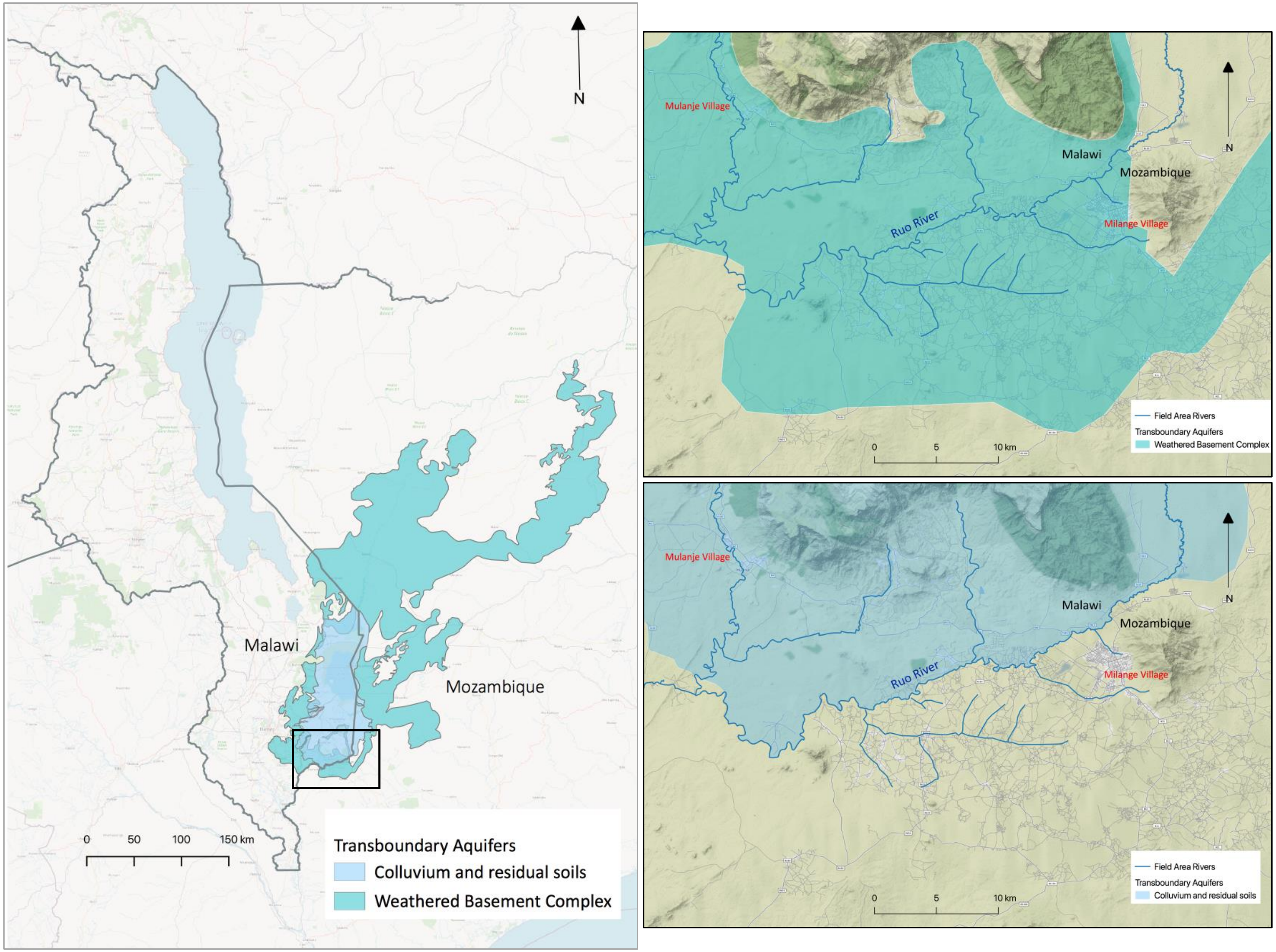


Figure 7.2 – Transboundary aquifers within the field area. (a) represents a colluvium aquifer and (b) a weathered basement aquifer that lies underneath

Recharge to the aquifers within the region is reported to occur primarily from direct rainfall infiltration and, where the aquifers are in hydraulic contact with rivers or lake water, by losses from surface water (Chavula 2012). Generally, the topographically high areas within the Basin around the Mulanje Massif and in the north of the basin near Lake Malawi/Nyasa provide the best recharge zones. Within the savannah, recharge tends to be more limited. Water quality within the Shire River Basin is variable (Banda, 2020). In some parts of the lower basin, high salinity from evaporation results in many boreholes and shallow wells being abandoned (Kalin *et al.* 2019). Deterioration of watercourses through pollution from agricultural runoff, sanitation, sewage and industrial wastes are also a problem (Smedley, 2004; Smith-Carrington, A.K, Chilton, 1983; Monjerezi et al., 2011a; Bath, 1980; Back et al., 2018).

7.4.2 Sample Collection and Analysis

A series of sampling locations were selected based on accessibility, known functionality of hand pumps, and location within the study area to ensure a wide range of area is covered. Permission from both the Mulanje (Malawi) and Milange (Mozambique) District Commissioners was obtained for the project.

Fieldwork involved the collection of stable isotopes and chemical samples from groundwater (community water supply boreholes (19 samples), hand-dug shallow wells (5 samples)) and surface water sources (rivers (12 samples)) (Figure 7.3). Temperature, pH, Total Dissolved Solids (TDS), Turbidity and Electrical Conductivity (EC) were measured on site using a portable multimeter (Model: HI-98194, Hannah Instruments, Woonsocket, RI, USA). Geographic information such as GPS coordinates and elevation were captured alongside well depth and water point functionality for groundwater points. All the 34 water samples collected were subjected to hydrochemical and stable isotopic analysis at the Ministry of Irrigation and Water Development (MoIWD) National Water Laboratory. A pair of acidified and nonacidified samples was collected from each sampling point using polyethylene bottles rinsed with deionised water prior to water sampling. The set of acidified sampling bottles was prepared using hydrochloric acid (HCl-20%) for cations (sodium as Na^+, potassium as K^+, magnesium as Mg^{2+}, calcium as Ca^{2+} and iron as Fe^{2+}) analysis, while the non-acidified set was meant for anions (carbonate as CO_3^{2-} and bicarbonate as HCO_3^-, nitrate as NO_3^-, sulphate as SO_4^{2-}, chloride as Cl^-) analysis. The water samples were tagged with location identifiers using waterproof stickers for proper chain of custody. Following collection, the samples were kept refrigerated at 4 degrees Celsius in specialised field cooler boxes and transported to the MoIWD laboratory. The water samples were filtered at the laboratory using 0.45µm filter membranes, also kept refrigerated (at 4 degrees Celsius) and away from direct sunlight to prevent photochemical decomposition before analysis.

Laboratory work involved analysis of a battery of cations and anions and stable isotopes (Deuterium (δD) and Oxygen-18 (δ18O)). CO_3^{2-} and HCO_3^- were determined by standard hydrochloric acid titration method, whereas Mg^{2+} and Ca^{2+} were determined by standard EDTA titration method, and Cl^- was determined by standard silver nitrate method. A flame photometer (Model: 410, Camlab, Cambridge, UK) was used to measure Na^+ and K^+ based on a flame photometry method, while an Ultra Violet (UV)/visible spectrophotometer (Model: DR/3000, Hach, Loveland, CO, USA) was used to measure NO_3^-, SO_4^{2-} and Fe^{2+} based on calorimetric and spectrophotometry method. The quality of the analysis process was assured and controlled by the use of standard blanks and duplicate samples as well as calibration of all instruments per standard instructions prior to both field and laboratory analyses. The accuracy of the analysis results was validated by calculation of ion-balance in compliance with an acceptable error of ±5%. All field and laboratory activities (onsite measurements, sample collection, transportation, holding, preparation and analysis) were conducted in accordance with International Standard Methods (ISM) (APHA, 2012).

Isotope samples were collected in specialised bottles for $\delta^{18}O$ and δD analysis using a Picarro isotopic water analyser (Model: L2110-I, Picarro, Santa Clara, CA, USA) at MoIWD Isotope Hydrology Laboratory (IHL) based on a laser spectroscopy method following international standard methods (IAEA, 2009). The water isotope samples were stored at 4 degrees Celsius, away from direct sunlight during transportation and holding at the IHL to prevent fractionation by evaporation. The Picarro isotopic water analyser was calibrated daily using heavy and light standards spanning the expected isotopic composition range of the water isotope samples. Additionally, daily control mid-range standard intermediate between heavy and light standards was used for further calibration. The precision (2σ) of the isotopic analysis was set at ±0.2‰ for oxygen-18 and ±2.0‰ for deuterium. The isotopic analysis results were quantified and validated using a Laboratory Information Management System (LIMS) software made specifically for the Picarro isotopic water analyser. The results were reported in delta values (δ) that represent parts per thousand deviations (‰) from the international V-SMOW (Vienna Standard Mean Ocean Water (Craig, 1961). The entire field and laboratory process involving sample collection, transportation, holding, preparation and analysis were carried out in line with IAEA international standard methods (IAEA, 2009).

7.4.3 Sample Interpretation

Bivariate ratio plots of $\delta^{18}O$ vs δD, δ18O vs altitude and D-excess vs $\delta^{18}O$ were plotted in Excel for borehole, shallow well and river samples. Samples were compared to both global and local meteoric water conditions by plotting a Global Meteoric Water Line (GMWL), defined as $\delta D = 8\delta^{18}O + 10$ by Craig (1961), and a Local Meteoric Water Line (LMWL) defined as $\delta D = 7.7\delta^{18}O + 9.5$. LMWL that was created using data from a weather station in Mozambique at Gorongosa, which was obtained from the GNIP database (8 samples) (IAEA/WMO, 2019). The single weather station in Mozambique was selected as it best represented the climate of the field area. This allowed for an interpretation of isotopic signatures, recharge location and type, the altitude effect, groundwater-surface water interaction, evaporation and vapour sources to be made.

The geochemical interpretation was undertaken using a combination of box plots, piper diagrams and spatial maps. A box plot of major ions and water quality parameters was plotted to understand the spread of ion composition and to identify if any water quality parameters were out with acceptable limits. A piper diagram presenting results from boreholes, shallow wells, and river water was plotted to identify dominant ion compositions and geochemical evolution trends. In order to investigate spatial distribution, groundwater and shallow well samples were plotted in QGIS based on their major ion compositions, which were identified using the piper diagram. A conceptual model was then developed utilising all results generated from the analysis undertaken to produce a holistic visual representation of the isotopic and geochemical situation within the field area, and to allow for clear understanding of the transboundary implications of the results.

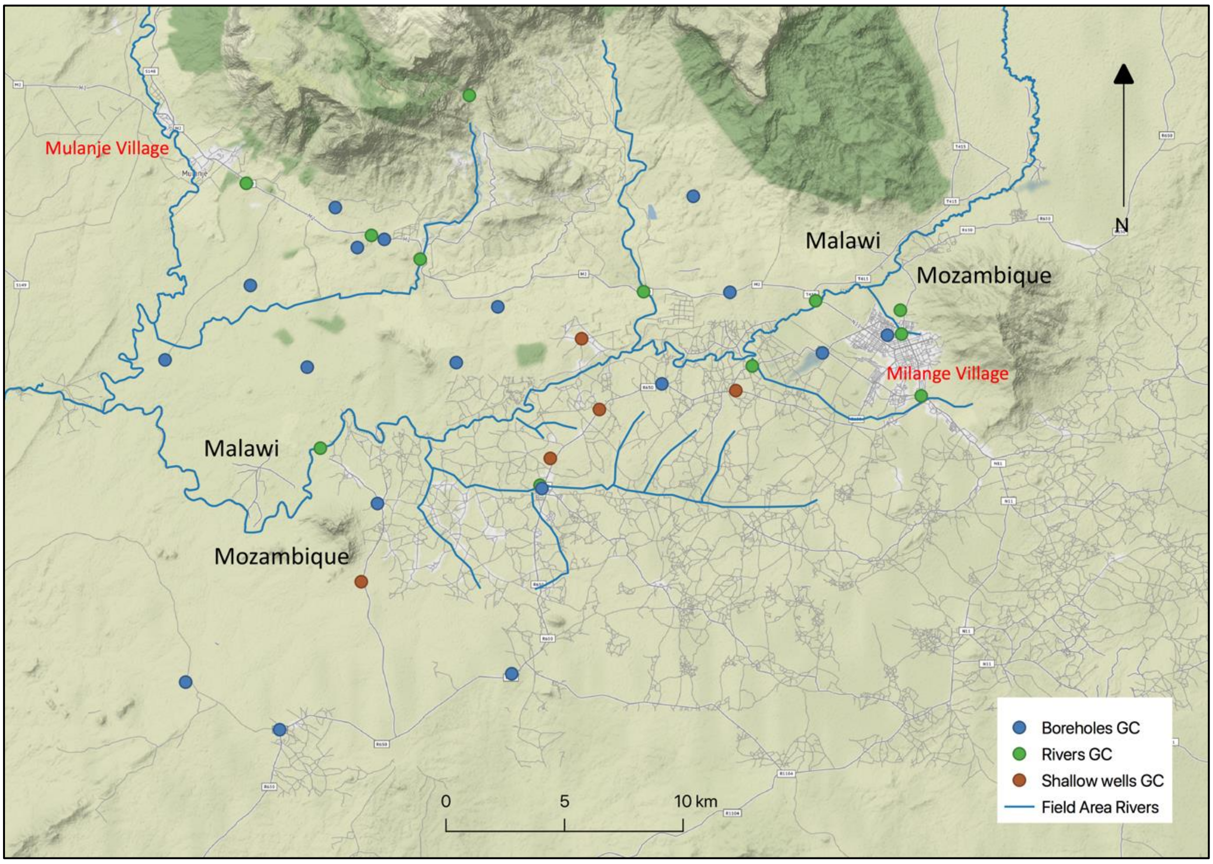


Figure 7.3 – Map of the sampling locations

7.5 Results

Geochemical variables measured were carbonate (CO_3^{2-}), bicarbonate (HCO_3-), chloride (Cl^-), sulphate (SO_4^{2-}), nitrate (NO_3^-), sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and iron (Fe^{2+}). Water quality parameters measured were hardness, alkalinity, pH, electrical conductivity, total dissolves solids, temperature and turbidity. Stable isotopes of δD and $\delta^{18}O$ were also measured.

7.5.1 Chemical composition, groundwater classification and water quality

Geochemical results are summarised in figure 7.4. The pH of all samples is slightly alkaline. Borehole pH ranges from 6.92 to 8.20 and from 6.88 to 8.44 in Malawi and Mozambique respectively. Shallow well samples have pH between 6.60 and 7.89 and river samples between 6.77 and 8.24. TDS is generally within WHO guidelines for drinking water quality (WHO, 2006). Some borehole samples have slightly elevated TDS values, of up to 410mg/l. Turbidity within the boreholes is very low (generally <1 NTU). However, it is elevated in river and shallow well samples, ranging from 0.6 to 80.4 NTU. Shallow well and river samples hardness values indicate that they are classified as ‘soft’. Boreholes range from soft to moderately hard (up to 168 mg/l) (WHO, 2006). Bicarbonate concentrations were found to be between 198mg/l and 3mg/l with the lowest values recorded in the river samples and highest values in the borehole samples.

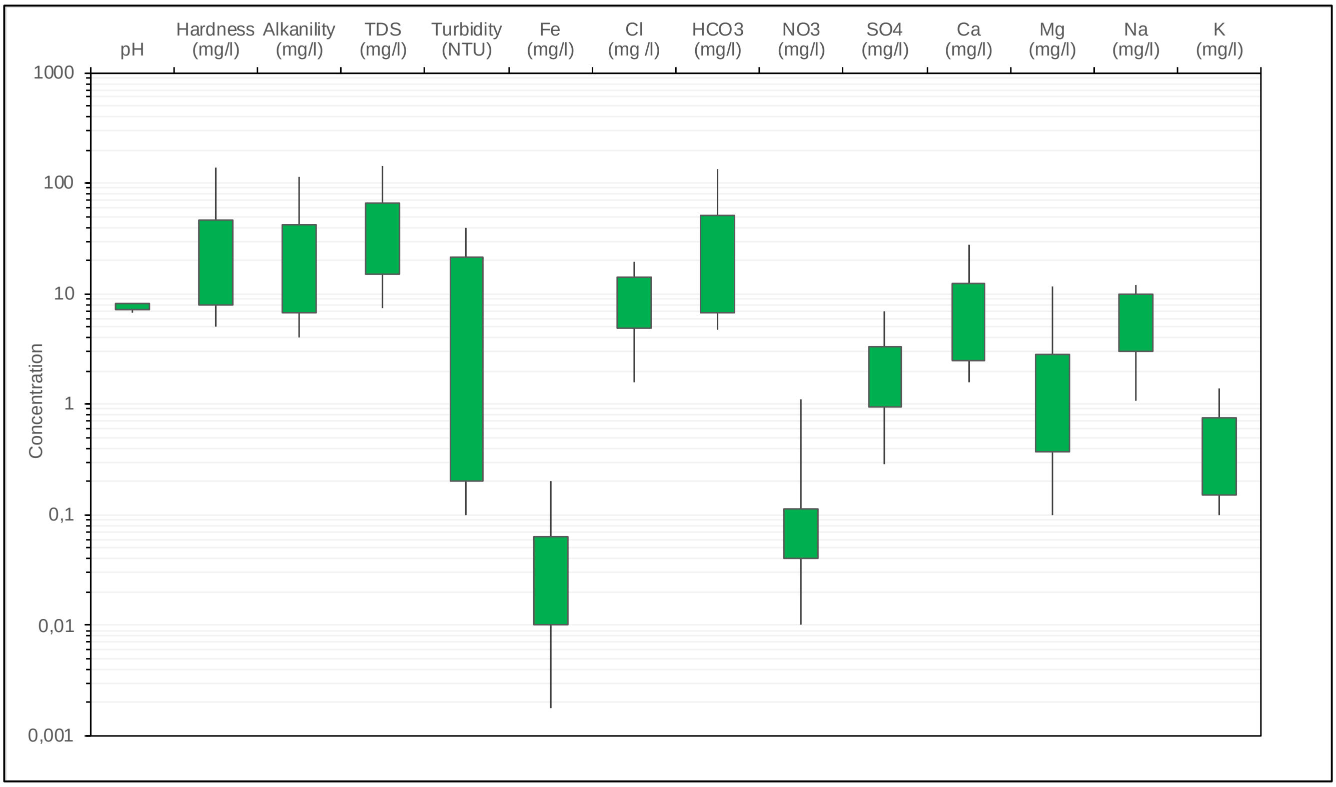


Figure 7.4 – Box plot of geochemical and water quality parameters

Chloride ranged between 2.7 and 20.9 mg/l in borehole samples, 2.6 and 15.0 mg/l in shallow well samples and 1.5 and 12.1 mg/l in river samples. Calcium ranged between 1.8 and 51.0 mg/l in borehole samples, 6.0 and 10.0 mg/l in shallow well samples and 0.9 and 7.5 mg/l in river samples. Sulphate ranged between 0.04 and 10.4 mg/l in borehole samples, 0.55 and 2.20 mg/l in shallow well samples and 0.25and 8.80 mg/l in river samples. Sodium ranged between 2.2 and 17.0 in borehole samples, 1.9 and 9.8 mg/l in shallow well samples and 0.8 and 7.0 mg/l in river samples. Nitrate, iron and potassium levels are very low (<1mg/l) throughout the dataset and are likely negligible. The full datasets for the geochemical analysis results of surface water and groundwater are presented in Appendix D.

Borehole, shallow well and river samples, classified using piper diagram, highlight differences between water types in terms of ion composition proportionally in terms of molar concentrations. Borehole samples are characterised by high levels of calcium, magnesium and bicarbonate relative to sodium, chloride and sulphate, categorising them as Ca/Mg-HCO_3 and Ca-Mg-Cl type groundwaters (figure 7.5a). These samples also exhibit higher levels of TDS than the river and shallow well samples.

The dominant cations in these samples may be sourced from the weathering of silicate minerals such as quartz, feldspar, plagioclase, amphiboles or pyroxenes, which are all present within the crystalline basement complex. Pyroxenes are a source of calcium and magnesium, amphiboles are a source of magnesium, calcium and sodium, biotite is a source of magnesium, potassium and sodium and feldspars are a source of calcium, sodium and potassium (Habgood *et al.*, 1963; Bath, 1980). Borehole samples from Malawi tend to plot slightly more within the Ca-Mg-Cl type. They also have TDS values lower than the samples from within Mozambique. It is likely water in boreholes in Malawi is less geochemically evolved (less silicate weathering) than in Mozambique, and therefore those in Mozambique are hydrogeologically “down gradient”.

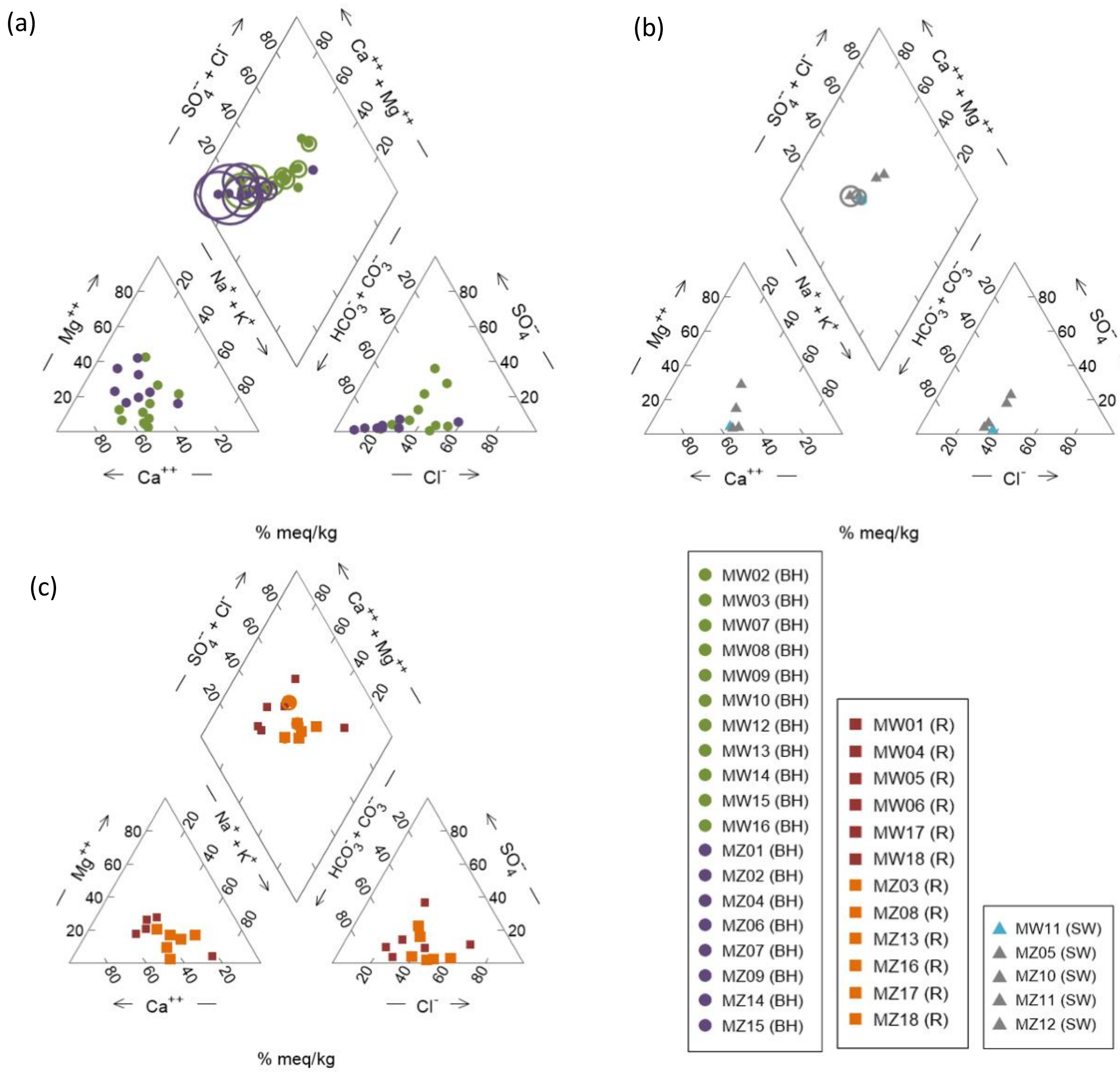


Figure 7.5a, b and c –*Piper diagram of borehole (BH), shallow well (SW) and river (R) samples with TDS circles (mg/l) for Malawi (MW) and Mozambique (MZ)*

Shallow well samples from Malawi and Mozambique were plotted in Figure 7.5b and plot primarily within the Ca-Mg-Cl type. The salinity levels of these samples (sodium and chloride) are higher than those from boreholes samples but are still low, indicating that there is some limited evaporation within the shallow groundwater. It should be noted there may also be an intermediate mixing between shallower and deeper groundwater denoting that the two aquifers are hydraulically connected alongside mixing between the river and shallow groundwater. River samples from

Malawi and Mozambique (figure 7.5c) plot within the Ca-Mg-Cl type and the Na-Cl type. These samples have higher levels of sodium than the boreholes and shallow wells. They also exhibit higher turbidity as is expected for increased undissolved content in surface waters.

7.5.2 Isotope Ratios

Stable isotopes, δD plotted against δ18O, were used to further develop a conceptual understanding of water source and transport. Results were plotted on the Global Meteoric Water Line (GMWL) and Local Meteoric Water Line (LMWL) (figures 7.6, 7.7 and 7.8).

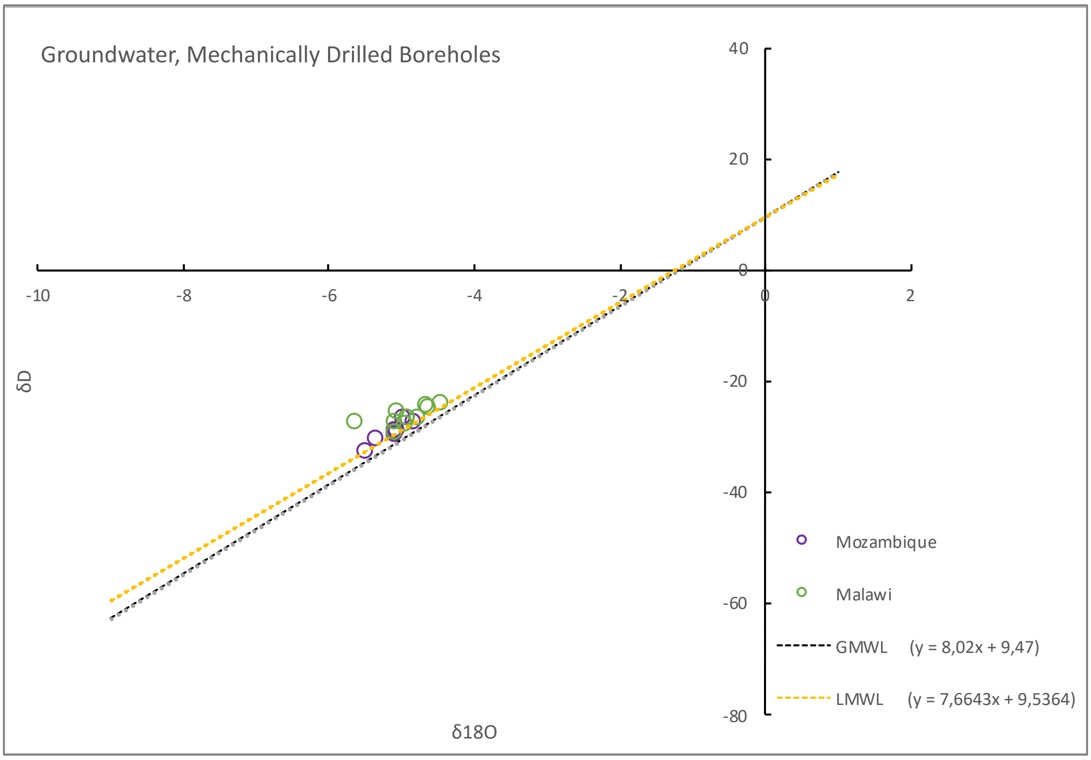


Figure 7.6 - Plot of δD and δ18O for borehole samples

Borehole (n=19 samples) δD ranged from -23.7 to -32 ‰ and δ18O ranged between -4.5 and -5.5 ‰. Calculated deuterium excess ranged from 11 to 18 ‰. Most borehole samples plot along or slightly above the meteoric water lines (Figure 7.6) providing strong evidence of non-evaporated local precipitation recharge to groundwater. The generally lighter isotopic composition and increased deuterium excess for borehole samples in Malawi suggest high-altitude isotopic signatures (snow can fall on the Mulanje Massif) compared with the Mozambique samples. This fits with the topography of the region and suggests that precipitation is recharging each part of the aquifer either side of the border.

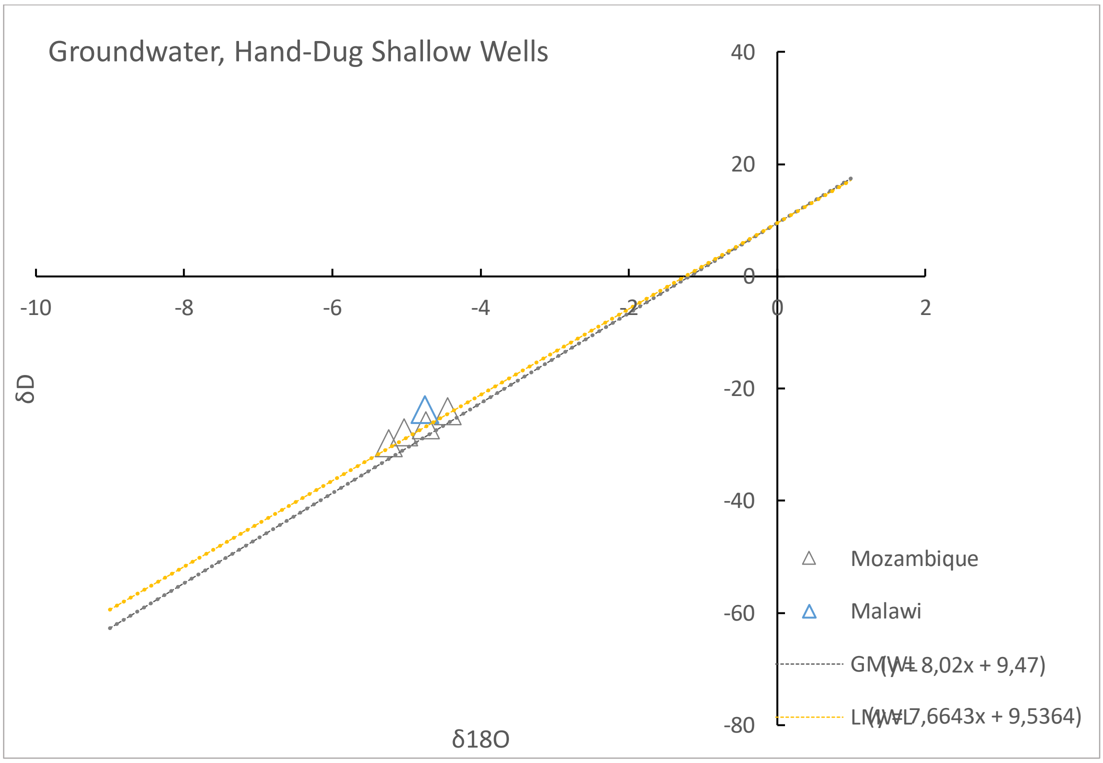


Figure 7.7 - Plot of δD and δ18O for shallow well samples

Shallow well (n=5 samples) δD ranged from -24 to -29.7 ‰. δ18O ranged between -4.5 and -5.2 ‰. Deuterium excess ranged from 11 to 14 ‰. The shallow well samples plot on a slightly shallower gradient to the LWML and GWML suggesting that these samples have been subjected to slight evaporation loss whilst still receiving non-evaporated local precipitation recharge (figure 7.7). Like the borehole samples, shallow well samples in Malawi exhibit an increased d-parameter and lighter high-altitude isotopic signatures than the Mozambique samples, consistent with topography.

River (n=12 samples) δD ranged from -26.1 to -38.9 ‰ δ18O ranges between -5.0 and -6.9 ‰. Deuterium excess ranged from 11 to 18 ‰. Isotopic signatures show that river samples exhibit the most evaporation loss with a shallower trend line gradient

(Figure 7.8). Given that the groundwater from borehole and shallow well samples exhibit very little evaporation, it is likely that recharge to the groundwater comes from precipitation and that groundwater feeds into rivers in the area. This is supported by a study by Kelly et al. (2019b) that discovered that the Ruo River is a gaining river with a baseflow index of 0.46 (Kelly et al., 2019b; Hiscock and Bense, 2005).

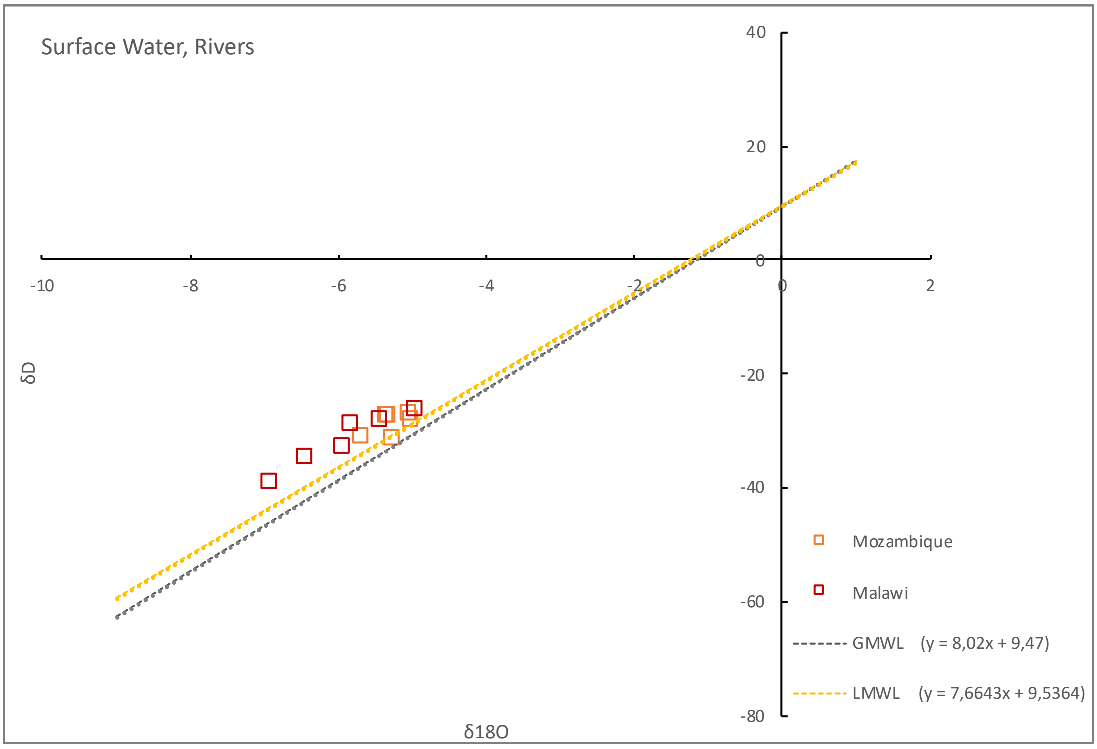


Figure 7.8 - Plot of δD and δ18O for river samples

7.5.3 Spatial Maps

Spatial maps of major ions from well samples were created to understand the spatial distribution of geochemical results (figure 7.9). Borehole and shallow well spatial maps of dominant ions (magnesium, calcium, bicarbonate, and chloride) show a general trend of ion enrichment from the north east down towards the south west, crossing the international border between Malawi and Mozambique. Geochemical interpretation indicated that silicate weathering was prevalent in the borehole samples. As water flows through an aquifer, its composition changes through interaction and reaction with minerals present within the rocks. It is likely that in figure 7.9 we are seeing the increase of basement complex rocks interacting with groundwater and weathering as they move through the aquifer from the north east, across the border to the south west. This interpretation is also consistent with known regional groundwater flow lines as reported by the Government of Malawi (1987). This is also supported by high TDS values in the boreholes samples that increase as you cross the border into the Mozambique portion of the basement aquifer; Near the recharge area, the groundwater exhibits lower TDS values but as the water flows through the aquifer it gains more dissolved substances thus increasing TDS values.

7.5.5 Conceptual Model

A conceptual model of the field area was developed using the results from the geochemical and isotopic interpretation (Figure 7.10). A comprehensive understanding of the groundwater dynamics of a transboundary aquifer system is needed for any successful transboundary cooperation policy (Al-Gamal, 2011). A critical step in this understanding is the development of a conceptual model. This is a simplified, qualitative representation of the complexity found in a natural system that represents its most essential characteristics, and is the basis on which more complex, quantitative or numerical analyses are formulated (Gillespie et al., 2012). Conceptual representation gives policymakers a simple understanding of the complexities of the system over which they must manage. Isotope and geochemical analysis lend themselves well to the development of conceptual models due to their relative simplicity and cost-effective implementation. If further study is warranted (e.g. the development of a full 3D groundwater flow model), then a conceptual model is a required tool to build this upon.

Figure 7.10 illustrates the Ruo Transboundary System, a two-layered aquifer system that is hydraulically connected to surface waters and receives local precipitation recharge. The deepest aquifer is composed of weathered basement complex formed of gneiss and granulite with mineralogy rich in calcium, magnesium, bicarbonate and chloride from the presence of pyroxene, biotite, amphiboles and feldspars. Saprolite weathering of the rock release calcium, magnesium, bicarbonate and chloride into the groundwater (Smith-Carrington and Chilton, 1983). Geochemical constituents in groundwater from weathering are greatest in Mozambique portion of the aquifer suggesting these waters are older than that of the Malawi portion. Groundwater in this aquifer is therefore likely to flow from Malawi across the international border into Mozambique. Isotopic signatures of these deeper groundwater boreholes show evidence of non-evaporated local precipitation recharge on both sides of the border with samples in Malawi exhibiting higher-altitude isotopic signatures than lower-altitude Mozambique samples.

The shallow aquifer within the Malawian border is composed of colluvium (unconsolidated sediments) and exhibits a higher ratio of chloride within its water composition as compared to the borehole samples. This is likely due to dry seasonal evapotranspiration within unconsolidated sedimentary aquifers in the Shire River Basin (Monjerezi *et al.*, 2011b). Isotopic signatures of this aquifer support slight evaporation loss whilst still receiving non-evaporated local precipitation recharge. Similarly, shallow groundwater within the Mozambique side of the field area also exhibits a higher ratio of chloride within its water composition as compared to the borehole samples from the same aquifer. Like the borehole samples, shallow well samples in Malawi exhibit higher-altitude isotopic signatures than the lower-altitude Mozambique samples. It is likely that there is some mixing between the deeper (borehole) samples and shallower (shallow well) samples.

River samples from the Ruo and its tributaries exhibit Ca-Mg-Cl type with any Na-Cl water compositions attributed to agricultural activity or evaporation. These samples exhibit higher levels of Na than the boreholes and shallow wells also exhibit higher turbidity as is expected for increased undissolved ions in surface waters. Isotopic signatures of river water support minor evaporation loss with a shallower trend line slope. Given groundwater from boreholes and shallow wells exhibit very little evaporation, it is likely that recharge to the groundwater comes from precipitation and that groundwater provides baseflow to rivers in the area. This is supported by a study by Kelly *et al.* (2019) that calculated the baseflow index of the Ruo River and concluded it is a gaining river.

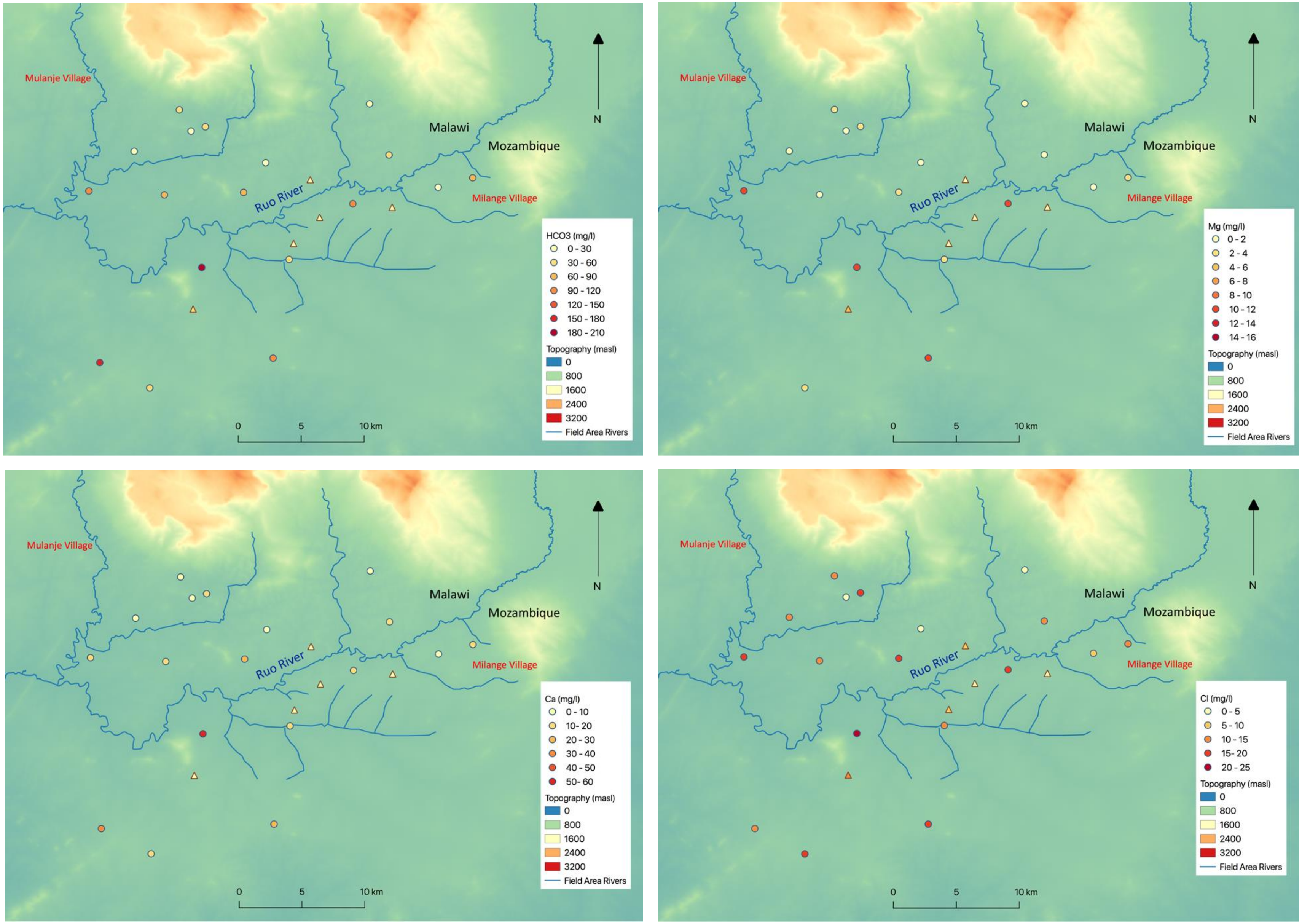


Figure 7.9 - Spatial Maps of HCO3, Mg, Ca and Cl with borehole (circles) and shallow well (triangles) samples

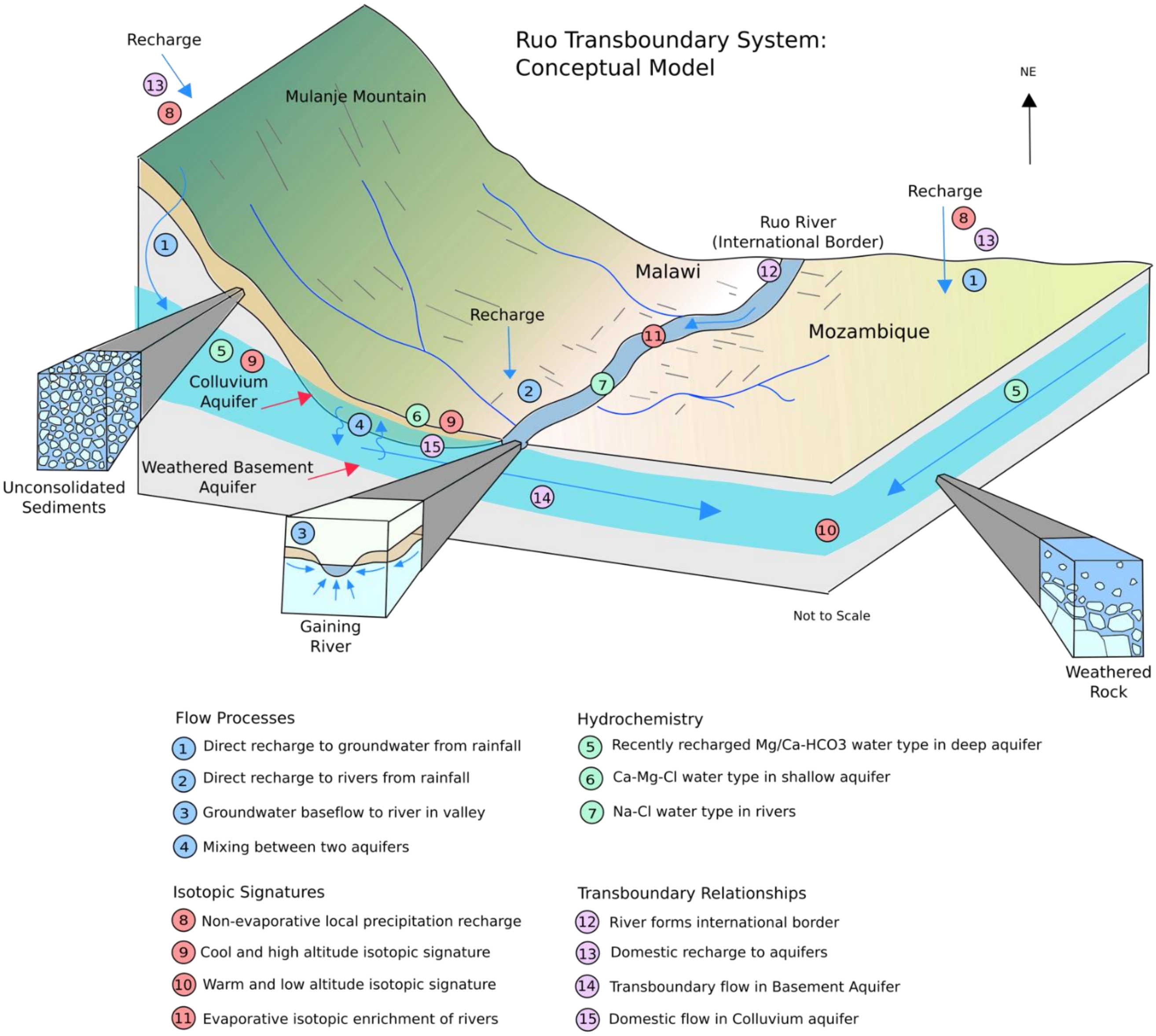


Figure 7.10 – Conceptual model of field area highlighting flow processes, hydrochemistry, isotopic signatures and transboundary interactions

7.6 Discussion

Isotope and geochemical analysis improved understanding of transboundary interactions in a geologically complex setting. In countries like Malawi where water resource monitoring networks are underfunded, if at all, this kind of analysis can provide a cost-effective approach for understanding groundwater flow and interactions when compared with data intensive groundwater modelling and cost intensive aquifer analysis such as borehole drilling and pumping analysis.

It is important to consider what management strategies are needed to manage the Ruo transboundary system in a sustainable manner. Results showed there is transboundary groundwater flow from Malawi into Mozambique. Recharge to the groundwater aquifers comes from local precipitation. Flow in the Ruo, a shared river that forms the border between the two countries, is maintained by baseflow from transboundary groundwater. These transboundary interactions need to be taken into consideration within an on-going management strategy. Results indicate there is no current wide-scale water quality issue in regards to iron and nitrate, although the area is at high risk to develop this. Previous research (Fraser et al., 2020c) also suggested that there is potential water stress due to over-abstraction within the area, although this was not observed within the field.

In 2019, the area depicted in this study was hit by extreme flooding due to Cyclone Idai. A similar flood event happened 2015 and between 1967 and 2018, Mozambique and Malawi experienced 36 and 38 flooding events, respectively (Shela et al., 2008). The Climate Justice Fund: Water Futures Programme in collaboration with the NGO CARE International carried out emergency relief water point rehabilitation for 665 wells across 10 districts including Mulanje, finding around 30% of boreholes were contaminated with E-Coli. During frequent flooding events increased groundwater levels and transport of faecal matter from nearby pit latrines or agricultural activity is another risk within the sphere of influence of boreholes (Kalin et al., 2019). Although not tested, it is suspected that the field area is also affected by e-coli contamination of boreholes due to their close proximity to nearby pit latrines. A transboundary management strategy within the area should take this into consideration and ensure it considers the impact from flooding as a transboundary consequence.

Recent global circulation and downscale modelling of combined surface water – groundwater systems predicted the impacts of climate change on water resources within the adjoining Shire River Basin to 2080 (Kawala, 2020). Results indicate the basin is expected to experience a temperature increase of 1.9 degrees C by the end of the century alongside a 15% increase in rainfall (Kawala, 2020). Furthermore, an increase of up to 24% in blue water flows (water found in aquifers, lakes and dams) is likely in the southern portion of the catchment (Kawala, 2020). These predictions should be carefully considered to also inform an agreed transboundary monitoring and management strategy.

Previous research identified that the Ruo Transboundary Aquifer System exhibits areas of groundwater quality and quantity concern at the national level (Fraser *et al.*, 2020c). For this sort of transboundary aquifer, international (government to government) cooperation and management are often required. This is usually done through an international transboundary agreement or an international institutional governance mechanism. International agreements over shared groundwater, however, are still in their infancy and are often difficult and time-consuming to develop (Rivera and Candela, 2018). Furthermore, the legal mechanisms to facilitate these agreements are limited. As there is already evidence of local scale transboundary cooperation in within the field area, a case could be made to substitute a national level agreement for district-level management.

The Malawi District of Mulanje, situated on the south-east border between Malawi and Mozambique is party to semi-regular meetings with the neighbouring Mozambique District, Milange. Representatives from the two districts meet and discuss shared issues such as trade, border control and management of their shared river, the Ruo, that runs along the border between the two districts (and forms the national boundary between Malawi and Mozambique).

A strong case can be made for the addition of transboundary groundwater to be added to this working group's mandate. An informal local agreement over the use and management of transboundary aquifers in Malawi might include clauses for agreed monitoring strategies, regular exchange of data, joint monitoring of boreholes and rivers, the inclusion of local stakeholders such as communities and local businesses. It could also meet during times of flooding and drought to discuss mitigation and adaption strategies for water security.

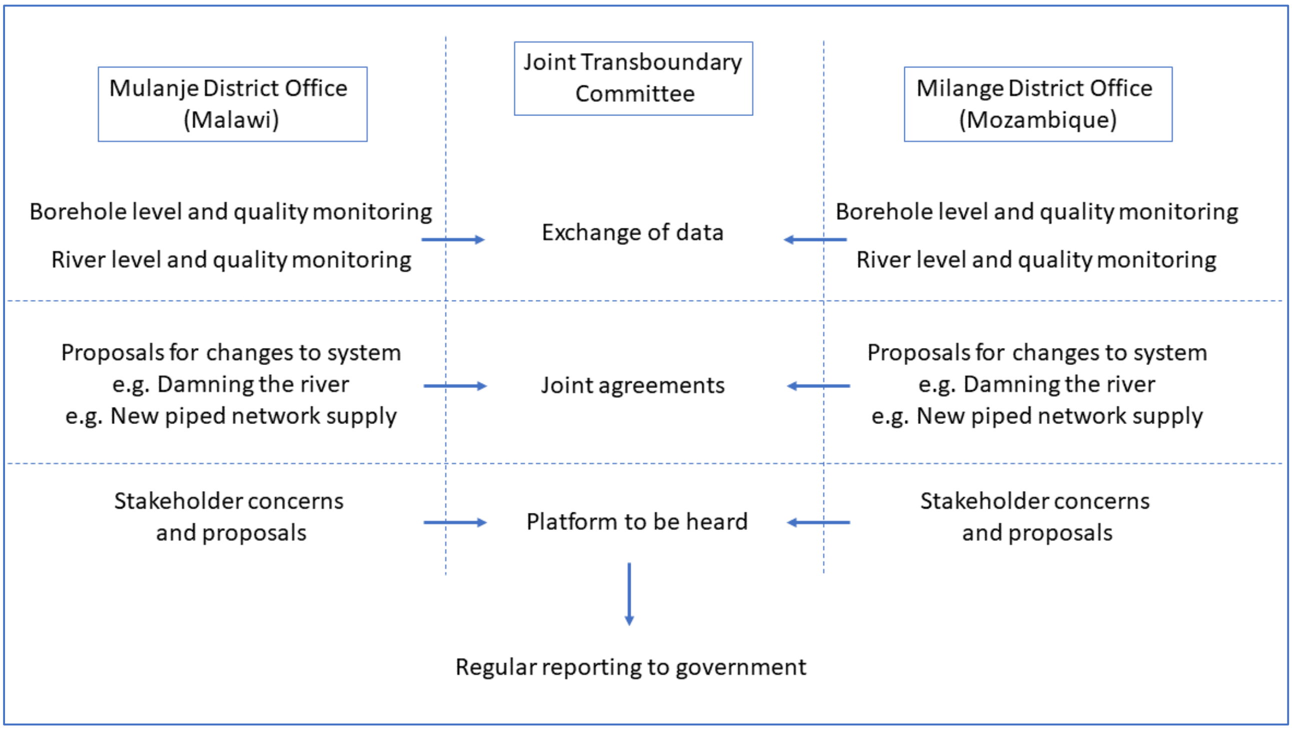


Figure 7.11 – Theoretical framework highlighting role of a potential joint transboundary committee managing the Ruo transboundary system

Figure 7.11 depicts a model of how such a committee may function and what purposes it could serve. This approach may be particularly effective within this case study as water supply in both Malawi and Mozambique is decentralised to local district offices (Ferguson and Mulwafu, 2004 and Inguane et al., 2014). The joint committee acts as a platform to facilitate joint agreements over water usage, enable the regular exchange of data and provide an outlet for local stakeholders to raise their concerns relating to potential water quality and quantity issues. Aided with the conceptual understanding developed here, this committee can be empowered to make decisions on the management and use of their transboundary resources. We propose activities within the committee be built around the conceptual model in Figure 7.11, ensuring that land-use change does not impact recharge rates, groundwater abstraction does not impact river levels, and that contaminated water is not flowing from one country to another. If monitoring suggests an escalation of reduced water quality and quantity, it could provide an effective mandate for the

Malawi and Mozambique government to cooperate to establish a full international transboundary agreement.

7.7 Conclusions and Recommendations

The Ruo transboundary aquifer system, spanning Mulanje district in Malawi and Milinge district in Mozambique, is a hydraulically connected system to the transboundary Ruo river, including tributaries and two transboundary aquifer units. Groundwater and surface water samples were collected within the Ruo Basin and analysed for isotope and geochemical parameters. Interpretation indicates the Ruo River, that forms the border between Malawi and Mozambique, is fed by baseflow from groundwater in the shallow colluvium aquifer while deep groundwater from the weathered basement aquifer moves across the border from Malawi into Mozambique. These two hydro-stratigraphic units are connected, and there is mixing between the two transboundary aquifers. Recharge to the system comes from precipitation on both sides of the border. Data for this study were collected during a one-month period, and longitudinal monitoring is needed to confirm that transboundary interactions are not subject to seasonal or annual variations. It is recommended that collaborative monitoring is undertaken over a period of at least 3 years in order to validate the transboundary interactions presented in this paper.

Any future agreement should focus on sustainable development and management of the Ruo transboundary system to ensure water quality and quantity does not diminish. Furthermore, it should consider the potential impacts of climate change (and increased potential for flooding/drought that comes with it) within its scope. The conceptual model presented here provides an understanding of the system and can aid in cross-border discussion between stakeholders. In the absence of an international transboundary agreement between Malawi and Mozambique, it is proposed that monitoring and management of the system is undertaken by an already established joint transboundary committee at the local level, governed by the district office on either side of the border. Duties of the committee should include planning of monitoring, exchange of relevant data, and the establishment of joint informal agreements over the use of the transboundary basin.

7.8 Postface

The final chapter answered RQ4 'what role geochemical and isotopic analysis might play in assessing the transboundary nature of an aquifer?' It utilised the Mulanje hotspot as a case study. A month long field campaign was conducted in the Mulanje District of Malawi and the neighbouring Milange District in Mozambique to collect water samples from surface and groundwater sites. 36 samples were collected and analysed for isotope and geochemical parameters (SO10). An interpretation of the results of the analysis highlights that the river that runs through the field area is fed by transboundary groundwater and that there is indeed transboundary groundwater flow across the border that flows from Malawi into Mozambique. A conceptual model of the transboundary water interactions was developed (SO11). Finally, a discussion of appropriate management of the transboundary aquifer was presented. It is recommended that management of this transboundary system is undertaken at the local scale ensuring regular monitoring of groundwater and surface waters and cross border exchange of data.

This chapter concluded the 4 main research chapters of this thesis. The next chapter will now summarise all conclusions made through this research and present recommendation for future research and practice.

8 Conclusions and Recommendations

This thesis answered the research aim to investigate the role that national scale transboundary aquifer assessments can play in sustainable water resources management and establish ways in which national scale transboundary aquifer assessments can be conducted, advocating for multi-scale transboundary aquifer management. This aim came from the understanding that there is a severe lack of transboundary aquifer identification and assessments at the national and local level. In addition to this, there were no available methodologies to identify zones to identify zones of transboundary concern for more directed management that encompass water quality and quantity factors. This thesis addressed this aim within the overall theme of increasing the understanding of transboundary aquifers in order to achieve Sustainable Development Goal 6.5.

To address this research aim, 4 individual research questions were answered through the thesis, each of which had multiple specific objectives attributed to them (figure 8.1).

A case study were used to assist in addressing the overall research aim. Malawi was selected as part of the conditions of the scholarship funding from the Scottish Government Water Futures Programme for this PhD. Malawi also posed an interesting study area due to its issues with water availability and its geographical position as a landlocked country, thus having multiple transboundary neighbours.

The overall conclusions from this thesis are presented below. Particular attention has been paid to how each chapter achieved the individual RQs and SOs. An integrated discussion is then presented that pulls together the main conclusions and messages of the thesis and to provide a discussion on the next steps for transboundary management within Malawi. Finally, a series of recommendations for further practice within the transboundary aquifer field alongside recommendations for further research are given.

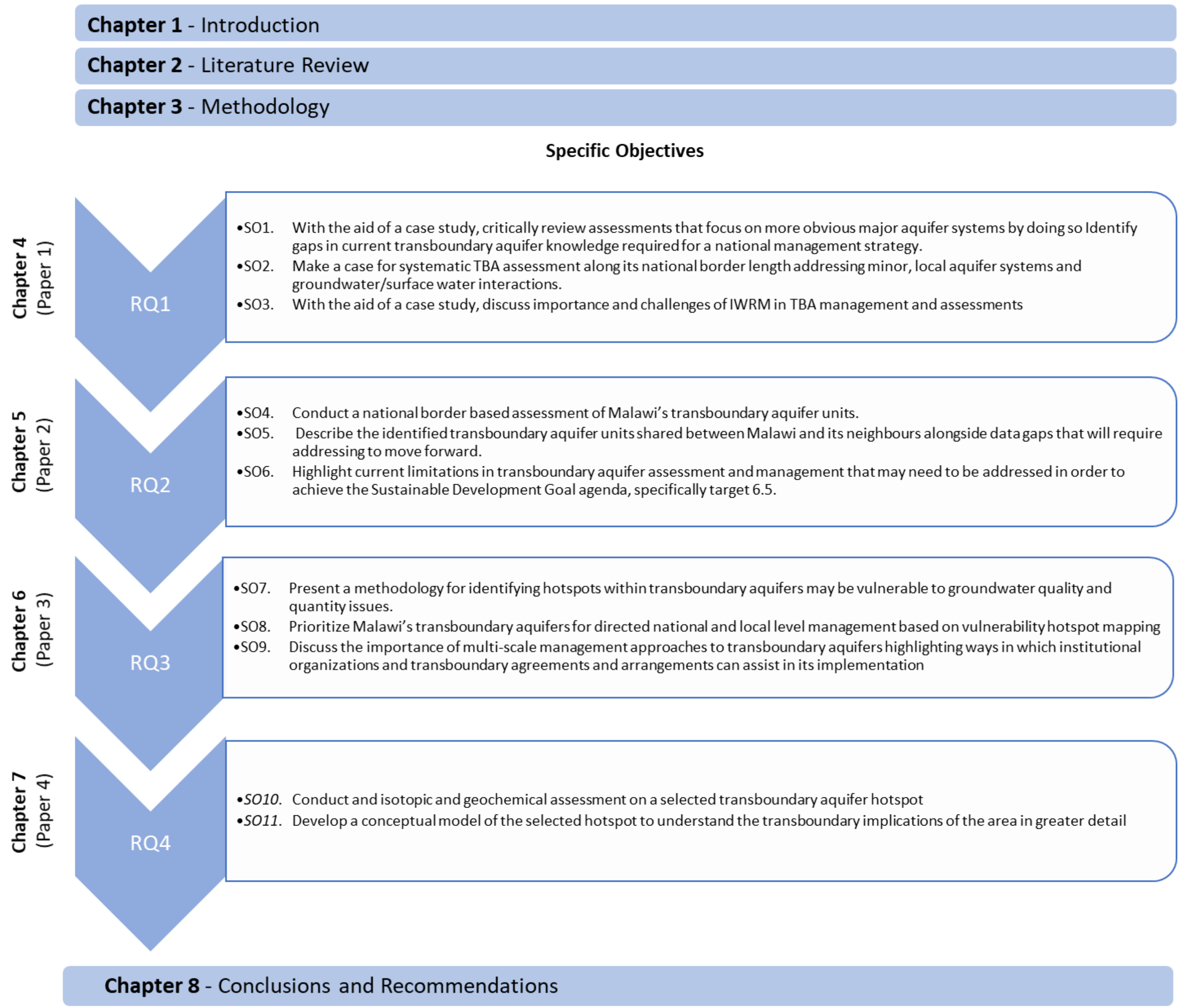


Figure 8.1 - Thesis roadmap, highlighting the research questions and specific objectives addressed in each thesis chapter

8.1 Summary of Key Findings

1. Chapter 4 answered RQ1. Chapter 4 achieved SO1 of RQ1 by illustrating that the status of transboundary aquifer assessments in Malawi proved insufficient for a national scale management strategy. Misgivings included replying upon the regional focused previous assessments conducted through the GEF-TWAP. The detail lost in such a large scale assessment was found to not provide sufficient understanding for a national scale understanding of transboundary aquifers. Regional transboundary aquifer assessments in Malawi have neglected multiple important aspects including the discontinuous nature of the weathered and fractured basement complex, the differing lithology's and thus mineralogy breakdown of the basement complex, and the presence of small scale alluvial and colluvium aquifers along river plains. Chapter 4 then achieved SO2 of RQ1 by showing that conceptualising more national and local scale transboundary aquifer complexity and encouraging countries to develop a strategy that systematically examines TBA systems along their national border at relevant scales will allow for more focused conjunctive policy creation and sustainable management of TBAs. SO3 of RQ1 was achieved by discussing the importance of these transboundary resources being managed within the IWRM scope and as part of hydraulically connected systems. Overall, current management frameworks in Malawi for water resources are built around surface waters catchments that are often misaligned with groundwater basins. Consequently, the groundwater aspect of the river basin is often managed indirectly to the rest of the hydraulic system. Fostering institutes that cooperate conjunctively on hydraulically linked surface and groundwater management on both the local, national and international scale is advocated to move forward with IWRM within the SADC. A recent development in progress on groundwater management within the region is the establishment of the SADC-GMI that aims to support the sustainable management of groundwater at national and transboundary levels across SADC member states. The national border based approach to transboundary aquifer assessments proposed in this chapter supports this initiative.

2. Chapter 5 answered RQ2. Chapter 5 presented an approach to assess transboundary aquifers at the national scale and applied it to the Malawi case study. This approach has 3 stages. The first, involves data acquisition, geological lithology correlation, hydrogeological unit correlations and then the delineation of transboundary aquifer. Stages 2 and 3 involve a risk hotspot analysis of identified aquifers for prioritization and then further assessment of those prioritised aquifers (see chapters 6 and 7). This chapter achieved SO4 of RQ2 by identifying 38 transboundary aquifers shared between Malawi and its neighbours utilizing a national border-based approach. This is a large increase from a previous estimate of 3 TBAs and is due to the consideration the discontinuous nature of the weathered and fractured basement complex, the differing lithology's and thus mineralogy breakdown of the basement complex, and the presence of small scale alluvial and colluvium aquifers along river plains within its assessment. This chapter described the aquifer types and currently data gaps and subsequently achieved SO5 of RQ2. These 38 aquifers are composed of weathered and fractured basement rock, karoo sediments and basalts, river alluvium and unconsolidated colluvium. A lack of borehole monitoring data (water levels and quality) is a severe limitation in understanding the transboundary flow of these aquifer. Furthermore, cross border data harmonization and a lack of mapping consistency across borders present challenges in TBA assessments like this one. Transboundary aquifer assessment is essential in the drive to achieve the SDGs and this chapter concluded by identifying current limitations in transboundary aquifer assessment and management that may need to be addressed in order to achieve the Sustainable Development Goal agenda, specifically target 6.5. By doing so, it achieved SO6 of RQ2. SDG target 6.5.2 specifically refers to transboundary cooperation in assisting the implementation of IWRM. However, the target is potentially premature and limited in its approach. The SGD 6.5 target indicator calls for the percentage of a basin under an operational agreement to be calculated. By taking a basin approach, there is a risk of negating groundwater resources that do not align with surface water basins. Furthermore, basin wide management is often not the best approach

for transboundary management, especially for more local scale transboundary aquifers. Operational agreements of the manner the target is requesting will also require strong governance and institutions to implement them. Aligning the SGD's indicators with already in-place institutional mechanisms will speed up this process. However, there are relatively few institutional mechanisms designed to manage transboundary groundwater resources, particularly within the SADC context. Finally, transboundary resources are still not well understood, especially at the national and local level. Without first identifying and assessing all transboundary aquifers, the operational arrangements that the SDGs call for, cannot be put in place.

3. Chapter 6 answered RQ3. The chapter achieved SO7 of RQ3 through presenting a new methodology to identify transboundary aquifer hotspots and applied it to the Malawi case study. Fuzzy logic and GIS overlay analysis were used to pinpointed specific areas within Malawi that may be at transboundary risk to reduced water quantity and quality. 6 layers of data were used in the analysis including water point type, land use, hydrogeology, number of users per water point, distance to pit latrine and seasonal fluctuation of water supply. A spatial map of the results was produced highlighting key areas of transboundary risk which were then split in to local and national scale hotspots, thus achieving SO8 of RQ3. Results indicated that there are 3 transboundary aquifers considered to be at a high risk at the national level for over abstraction and contamination which may require formal transboundary agreements. There are a further 11 hotspots on smaller scale transboundary aquifers that could be managed at the local level. These aquifers can now be prioritised by the Malawian Government for further assessment and management efforts. This chapter achieved SO9 of RQ3 by considering the importance of multi-scale management within the transboundary context. No two aquifers are the same, and thus the use of an aquifer should inform how it is managed. This can range from regional river basin scale management all the way down to local communities and stakeholders. Classifying what type of management is required of an aquifer

is particularly important in countries like Malawi, where resources and financial reserves are limited. Within a transboundary context, it is even more essential to ensure that the selected management type is established in cooperation with neighbouring countries. Available resources should be directed to aquifers in most need for management on a case by case basis. Regional transboundary aquifer assessments can be useful in determining which aquifers may need to be managed at an international level, under inter-governmental organizations like ZAMCOM. National border based assessments can inform international (government to government) and local level (community to community/district to district) management where both formal agreements and informal arrangements have their place.

4. The final research chapter of this thesis answers RQ4. Chapter 7 examined the role that geochemical and isotopic analysis can play in assessing the transboundary nature of an aquifer. An isotopic and geochemical assessment was conducted on a selected hotspot identified from chapter 6 through SO7 and 8. A month long field campaign was conducted in the Mulanje District of Malawi and the neighbouring Milange District in Mozambique to collect water samples from surface and groundwater sites. 36 samples were collected and analysed from a transboundary aquifer system (composed of weathered basement complex and colluvium deposits) for isotope and geochemical parameters. Geochemical variables measured were carbonate (CO_3^{2-}), bicarbonate (HCO_3-), chloride (Cl^-), sulphate (SO_4^{2-}), nitrate (NO_3^-), sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and iron (Fe^{2+}). Water quality parameters measured were hardness, alkalinity, pH, electrical conductivity, total dissolves solids, temperature and turbidity. Stable isotopes of δD and $\delta^{18}O$ were also measured. This field campaign and the interpretation of its results achieved SO10 of RQ4. Interpretation through box plots, piper diagrams, bivariate ratio plots and spatial maps indicate (1) the Ruo River that forms the border between Malawi and Mozambique is fed by groundwater from a shallow colluvium aquifer on the Malawi side and a weathered basement aquifer on the Mozambique side; (2) deep groundwater

from a weathered basement aquifer moves across the border from Malawi into Mozambique; (3) there is mixing between two aquifers in the field area; and (4) recharge to the system comes from precipitation on both sides on the border. A conceptual model was developed in order to present the transboundary nature of the system in an accessible format for involved stakeholders and thus achieving SO11 of RQ4. These results have implications for management of the transboundary system. The Malawi District of Mulanje, situated on the southeast border between Malawi and Mozambique is party to semi-regularly meetings with the neighbouring Mozambique District, Milange. A strong case can be made for the addition of transboundary groundwater to be added to this working groups' mandate. An informal local agreement over the use and management of transboundary aquifers in Malawi might include clauses for agreed monitoring strategies, regular exchange of data, joint monitoring of boreholes and rivers, the inclusion of local stakeholders such as communities and local businesses. It could also meet during times of flooding and drought to discuss mitigation and adaption strategies for water security.

8.2 Thesis Contribution to Knowledge

This thesis has contributed knowledge to the wider international community through published literature, to the national Malawi SDG agenda through providing data and a more in depth understanding of their transboundary aquifers, and to local level transboundary management and understanding within the Ruo Transboundary Aquifer System. More specifically it has contributed the:

- Identification of key research gaps within the transboundary aquifer field in Malawi and the broader Southern African Development Community region.

- Development of a new methodology for assessing transboundary aquifers along the border at the national scale.

- Increased understanding of Malawi's transboundary aquifer delineation and hydrogeological characteristics. Identification of 38 transboundary aquifers as opposed to 3 in previous assessments.

- Increased understanding of the importance of multi-scale transboundary aquifer assessment and management

- Development of a new methodology to identify transboundary hotspots within aquifers at the national and local scale that addresses both water quality and quantity concerns

- The application of a hotspot methodology to transboundary aquifers in Malawi; identification of national and local scale hotspots for prioritization.

- Improved transboundary aquifer assessment at the local scale within Malawi through the focused investigation of the Ruo Transboundary Aquifer System.

- Development of a local scale transboundary management structure for the Ruo transboundary Aquifer.

8.3 Moving Forward with Transboundary Aquifer Management in Malawi

The overall aim of this thesis was to to investigate the role that national scale transboundary aquifer assessments can play in sustainable water resources management and establish ways in which national scale transboundary aquifer assessments can be conducted, advocating for multi-scale transboundary aquifer management. Conclusions are clear: There is a role for national border-based transboundary aquifer assessments in increasing the understanding of transboundary water resources at the national and local scale; and prioritization within these aquifers is a valuable tool to direct often limited resources for management of transboundary aquifers in a strategic manner. Such approaches as the ones developed in this thesis will be critical to inform appropriate national management policies, international cooperation, and the development and implementation of science-informed TBA agreements that are workable. But with the new knowledge and understanding generated through the achievement of the thesis research and specific objectives, come the questions of how best to move forward.

Here, Malawi's current situation is examined in terms of transboundary management, cooperation and the likelihood of the country and its neighbours meeting SDG target 6.5 by 2030. The strict criteria of what constitutes an 'operational' transboundary agreement under SGD 6.5.2 is deliberated, parallels are drawn from the management of transboundary surface water within Malawi, financing barriers are discussed, and the benefits (or lack thereof) of acceding the UN or UNECE convention are addressed. Finally, it is proposed that the real workable solution may be to break away from the SDG model altogether.

8.3.1 Transboundary Cooperation under the SDGs

The assessment, vulnerability analysis and deeper understanding of Malawi's transboundary aquifers achieved through this thesis is alone not sufficient to achieve SDG 6.5; it is simply a stepping stone to getting there. If Malawi wants to achieve SDG 6.5 and in particular, meet target indicator 6.5.2, it must begin the process of developing cooperative arrangements with its neighbours over their transboundary groundwater resources (UN Water, 2017a). In order do this this, the Malawian Government will first have to take the results generated from this thesis and embed them within their internal understanding of transboundary aquifers. By officially acknowledging these newly identified aquifers, the government can move one step closer to sustainable management of them. However, important steps need to be taken to understand the hydraulic linkages between these transboundary aquifers and surface waters. Recharge and discharge zones linked to the aquifers must also be identified. These technical components are essential as the typology of the transboundary aquifer will dictate how it is managed under international law (Eckstein and Eckstein, 2005). Furthermore, integrated water resource management of transboundary groundwater is becoming increasingly important and should underpin transboundary aquifer assessments in order to achieve SDG 6.5 (UN Water, 2015). Secondly, the Malawi Government must consider the criteria under which an arrangement over transboundary water cooperation is judged: regular exchange of data, regular formal communication between parties, a joint management plan, and a joint body or mechanism to oversee the arrangement (UN Water, 2017a in McCracken and Meyer, 2018).

Regular exchange of data between Malawi and its neighbours is not as simple as it might sound. Often, ownership of data is contentious in these situations (SADC-GMI, IGRAC, IGS, 2019). Joint Information Management Systems (IMS) that can facilitate this level of data exchange and sharing can be expensive to develop and implement and currently Malawi does not have its own national IMS that hosts its water resource data (SADC-GMI, IGRAC, IGS, 2019; IGRAC and UNESCO-IHP. 2015a; Kalin et al., 2019). The Climate Justice Fund: Water Futures Programme has been working to embed the IMS 'mWater' within the Ministry of Agriculture, Irrigation and Water Development of the Malawian Government however this platform is intended to be only nationally-placed and thus unsuitable for transboundary data sharing (Kalin et al., 2019). IGRACs Global Groundwater Information System (GGIS - https://ggis.un-igrac.org/) and UNESCO-IHPs Water Information Network System (WINS - http://ihp-wins.unesco.org/#/) are two other open-access platforms that could be used by the Malawi Government however these platforms are often engaged at the project level rather than government to government management (IGRAC and UNESCO-IHP, 2015a). Furthermore, in order to exchange and share data, data must be generated in the first place. Monitoring data is a vital component in transboundary aquifer management to track the sustainability of the resource (SADC-GMI, IGRAC, IGS, 2019). Currently, Malawi's national monitoring borehole network is very limited with regards to it spatial spread and in the way data is collected and managed (IGRAC, 2020a). As of 2021, monitoring data is still collected and stored on excel, making it difficult to share and inform direct management practices.

Formal communication is an aspect of the SGD 6.5.2 target indicator requirements that Malawi may not struggle to meet. At the technical level, Malawi is very engaged with transboundary related projects facilitated throughout the region by the SADC-GMI and other organizations (SADC-GMI, 2018). Engagement through this PhD thesis is another example of the willingness to communicate on transboundary aquifer issues. Furthermore, Malawi is part of the Southern Africa Development Community and participate in regular region meetings and summits that discuss transboundary water issues amongst others (SADC-GMI, 2016). Malawi also participates as an observer in ZAMCOM meetings despite not acceding the convention (SADC-DW et al., 2018; ZAMCOM, 2019).

A joint management plan first requires robust transboundary aquifer assessment to understand the key pressures and concerns within the aquifer alongside identifying areas of potential action and intervention jointly (UN Water, 2017a; McCracken and Meyer, 2018). Although the contributions to transboundary aquifer assessment from this thesis are considerable, much work is still to be done in order to have enough data and understanding to create a management plan for these transboundary aquifers. In 2018, the Shire CONWAT Project conducted a transboundary diagnostic analysis and subsequently developed a Joint Strategic Action Plan for the Shire River Basin, that included the Shire River Alluvial transboundary aquifer (SADC-GMI, 2018; SADC-GMI and IWMI, 2019). Strategic Action Plans are often utilized to assist countries in developing a shared vision and set of joint actions to enhance benefits and reduce risks of water management. The Strategic Action Plan for the Shire River Basin-Aquifer System was a negotiated policy document for transboundary water management between the Republic of Malawi and the Republic of Mozambique. Its aim was to agree on action steps for joint management of the basin however this project concluded in 2019 and since, no progress toward cooperative management over the basin has happened, likely due to no available funding (SADC-GMI and IWMI, 2019).

The establishment of a joint body or mechanism to oversee a cooperative arrangement is key in ensuring accountability and proper procedure. Malawi thus far has struggled to develop joint commissions over its transboundary groundwater resources however, surface water has received more attention. In 2003 a treaty was signed by the Malawian and Mozambique Government on 'The agreement on the establishment of a Joint Water Commission' to improve responses to flooding in the basin (IWMI, 2015). In 2017, Malawi and Tanzania also signed the 'Convention on the Establishment of a Joint Songwe River Basin Commission between Tanzania and Malawi' (Development Aid, 2020). It is hoped that the lessons learnt in developing these surface water commissions will assist in the facilitation of their groundwater counterparts.

A major barrier to transboundary aquifer management and developing operational arrangements within Malawi is financing. Malawi consistently appears in the top 3 countries in the world with the lowest GWP per capita (World Bank, 2021). Financial resources for new and, often 'non-priority' initiatives such as the development of a transboundary agreement, are therefore very limited. This is coupled with reactive rather than proactive response to transboundary aquifer management concerns that the country, and many others like it, currently adopts. In Malawi, due to limited data availability, it isn't fully known or understood whether the current abstraction regime is causing direct stress on transboundary aquifers (Fraser et al., 2020b). Additionally, as water quality testing is scarcely done, pollution issues could be left unidentified (Rivett et al., 2018a; Rivett et al, 2018d). This 'out of sight, out of mind' narrative is consequential in these circumstances as financing transboundary aquifer management is often left low on the agenda of key stakeholders within Malawi. Indeed, these issues are not isolated to Malawi; there is only 1 example of a proactive transboundary agreement worldwide that was not prompted by concerns for the transboundary water level or quality (The Guarani Aquifer Agreement, signed in 2000) (Villar, 2020).

Motivated by the understanding that in some regions, needs are greater and financial recourses are more limited (UN Water, no date), SDG target 6a was developed. Over 80 per cent of countries from a 2016-2017 GLAAS survey said they had insufficient funding to reach national targets on drinking water and sanitation (UN Water, 2017b). The target asks for increased international cooperation and capacity building support to developing countries with regards to water and sanitation activities (Guppy et el., 2019; UN Water, 2015). Provided as aid in the form of grants or loans, the mobilization of additional financial resources could assist with the transboundary aquifer agenda of Malawi. However, this would likely require the Malawi government to allocate these funds to transboundary projects over other WASH priorities. The Scottish Government, through its 'Hydro Nation' agenda, has an international program that aims to share knowledge and collaborate with other countries to grow the international water economy (Scottish Government, nd). As part of this, the government aims to deliver projects with partners in key international territories. Malawi is one of these territories. The CJF: Water Futures Programme was one of these projects. Concluding in 2021, the Scottish Government now have the opportunity to take the lessons learnt through the CJF and move forward with funding key initiatives to support the embedding of knowledge generated throughout the project. Including transboundary aquifer management as a key focus could greatly assist in the development of the Malawi Governments transboundary aquifer management agenda.

The challenges that face Malawi in achieving operational agreements over its transboundary aquifers are abundant. Improved governance could come in the form of acceding the UNECE Water Convention or the UN Watercourse Convention (UN, 2014; UNECE, 2013; UNECE, 2014). Indeed, this would be more effective in other countries in the region also acceded the Conventions, in particular Malawi's neighbours: Mozambique, Zambia and Tanzania. However, the lack of success with regards to transboundary aquifer agreements facilitated under the UN/UNECE Conventions (there are still only 6 TBA agreements worldwide vs 600 surface water agreements) leave its effectiveness quite unconvincing; something isn't working (Burchi, 2018). Instead, indirect benefits of acceding these conventions, such as the increased awareness of transboundary aquifer management and the benefits it holds, may be more relevant in this case. This, in combination with Groundwater being the theme of UN Water World Water Day 2022 and the acceleration activities of the SDG Goal 6 targets, could help boost the importance of transboundary groundwater management to the attention of key policy makers within the Malawi Government (IGRAC, 2020b; UN Water, 2020a).

When examining Malawi's history with transboundary surface water agreements, not much hope is generated. As discussed, Malawi have a number of joint commission agreements over transboundary river basins. Aside from this, Malawi is also party to SADC Revised Protocol for Shared Watercourses (2000) that aims to foster close cooperation between member states over their shared water resources (SADC, 2003). However, a lack of more specific river or lake agreements suggests that the difficulty in transboundary cooperation may not be limited to groundwater. Lake Malawi is a large transboundary lake located between Malawi, Mozambique and Tanzania. The border between Malawi and Mozambique runs through the southern portion of the lake. The border between Malawi and Tanzania however is contested and conflict between the countries in the form of verbal threats and protests have occurred as recently as 2012 (Meyer 2012). Apart from regional and river basin treaties, no international agreements have resolved the contested delineation of Lake Malawi's border between Tanzania and Malawi (Lubner, 2015).

Through the SDG reporting cycles, when countries do report that an operational arrangement exists over a transboundary aquifer, it is often part of a larger and wider ranging transboundary river basin agreement. Although embedding transboundary aquifer management within river basin commissions can be unfavourable in many circumstances (e.g. when aquifer delineation does not align with surface river basin delineation), it appears to be a popular mechanism to manage both transboundary surface water and groundwater under the same umbrella (UNESC-IHO, 2016). A success story can be seen in the embedding of the Stampriet Aquifer System (STATS) Multi-Country Cooperation Mechanism (MCCM) in the ORASECOM' Groundwater Hydrology Committee (UNESCO-IHP, 2016; Ross, 2015; Haasbroek, 2018). The MCCM facilitates joint collection and exchange of data and information among the STAS countries to feed the STATS Information Management System. It is also hoped that, long term, the MCC will provide joint strategic assessment and advice to STAS countries on management issues relating to the STAS groundwater resources (UNESCO-IHP, 2016; Ross, 2015; Haasbroek, 2018). 93.2% of Malawi's territorial area and 86.1% of its population (MoAIWD, 2014) resides within the Zambezi River Basin and subsequently, Malawi was invited to sign the ZAMCOM Agreement; an agreement that sets out to foster cooperation from riparian states over the transboundary management of the surface water and groundwater within the basin

(SADC-DW/ Zambezi River Authority, 2008). This commission could be a valuable vessel for facilitating transboundary aquifer management throughout the Basin however Malawi is yet to accede the ZAMCOM agreement into policy (ZAMCOM, 2019). It must do so in order to move forward with transboundary cooperation at the river basin level.

8.3.2 A Different Route to Transboundary Cooperation

The SDG 6.5.2 target indicator reporting from the first round that took place in 2017 showed that only 17 countries hit the target and have all their transboundary basins covered by operational arrangements (UN and UNESCO, 2018). Preliminary results from the 2020 round of reporting suggest that this number has only gone up to 22 countries within the past 3 years (UN Water, 2020b). Progress has been limited and slow and insufficient groundwater knowledge has been identified as a key limitation to progress (UN Water, 2020a; UN Water; 2020b). Many have been critical of the SDG 6.5.2 methodology approach (McCracken and Meyer, 2018; Chaisemartin, 2020) and it is expected that this target will not be met by 2030, even with the potential for additional financing through SDG 6.a (UN Water, 2017a). A large reason why the target indicator has struggled to gain momentum is the perceived unattainable criteria for an arrangement for cooperation to be considered operational. The 4 criteria that must be met in order for an arrangement to be operational is too strict and constraining. The methodology calculation also omits countries from the scope of the SDG target who may be cooperating over their transboundary aquifer at a scientific and technical level but not at the political level. This lacks foresight as it is indeed often at the technical level where we see transboundary cooperation emerging from (Rivera and Candela, 2018). Furthermore, there are examples of TBAs that show effective cooperation at the technical level through MOUs to share data and this recognition is not given in the target methodology (e.g. the Lullemeden Aquifer System MOU (Burchi, 2018)). Why insist on meeting all 4 criteria if only 1 or 2 are needed in some scenarios? Indeed, this is a reflection of transboundary aquifers being very diverse and complex systems; no two are the same (Eckstein, 2012). The same can be said for the management strategy and cooperation that may or may not be required over it. Secondly, the time frame given for the development of transboundary aquifer operational arrangements is unreasonable given that in many areas of the world, we still don't even know where all of the transboundary aquifers are nor do we have sufficient data to understand the resource (UN Water, 2020b). The infancy of transboundary aquifer assessment and understanding is not accounted for in the target. To have the same criteria for a transboundary aquifer as a transboundary river or lake, where assessments and governance is arguably decades ahead (UNESCO, 2001; Eckstein and Sindico, 2014) does not reflect the reality of where we currently are with the science that needs to back these operational arrangements for transboundary aquifer cooperation. This target is, regrettably, ahead of its time in terms of transboundary aquifer cooperation.

Does Malawi actually need to achieve operational arrangements over all of its transboundary aquifers under SDG 6.5.2? Given the limited financial resources currently allocated to Malawi and its SDG 6.5 agenda (and other limitations discussed), it may be worth focusing on more achievable targets. If Malawi wants to move forward with realistic targets for transboundary aquifer cooperation, the Government might instead choose to focus on two things:

(1) Technical agreements over data collection and sharing in order to understand their shared aquifers in more detail but to also monitoring their status closely. This is particularly relevant to the Malawi case study because, as of yet, there are no strong indications of transboundary groundwater conflict, over abstraction or contamination (Fraser et al., 2020c). Prioritizing the transboundary aquifers that are at higher risk to developing future problems (as identified in chapter 6 of this thesis) would be a logical place to start. Monitoring these aquifers closely can allow for potential pressures on the systems to be identified early, before they escalate into full blown transboundary issues. If, down the line, a problem arises, this then may trigger the need for a more robust management agreement.

(2) Develop capacity building and cooperation at the more local level. Often, transboundary aquifer impacts are only going to be felt at the local level, close to the

border. This is because the impacts of aquifer drawdown and contamination are often only seen within a few kilometres of the source (Puri, 2021). Engaging stakeholders at the local level can therefore allow those directly impacted by transboundary issues to play a key role in management with communities residing close to the border taking the lead in developing and executing management practices (Daly et al., 2016). Water resource management in Malawi is decentralized and therefore passing down transboundary management responsibility to District Water Offices, who already manage surface water resource units, may allow for a more effective and directed management response where its specifically needed (Truslove et al., 2020; Ferguson and Mulwafu, 2004; Inguane et al., 2014).

8.3.3 Indirect Implications of TBA Assessment and Management

The benefits of increased transboundary aquifer delineation and assessment in regards to transboundary cooperation have been clearly demonstrated throughout this thesis. However, the non-direct benefits may not be as obvious. Across Africa, transboundary aquifers underlie 40% of the continent, and 33% of the population (381 million) live on TBAs (Nijsten et al., 2018). In Malawi, this is even more at >50% (Fraser et al, 2020c). Indeed, in these cases, transboundary aquifer management is also beneficial for the national water management agenda as large proportions of water resources on the domestic level can be managed through transboundary cooperation.

The opposite can also be said; the SDG agenda with regards to other targets within Goal 6 such as improved water quality, water use efficiency reduced pollution to watercourses, adequate sanitation and hygiene, where financing may be more readily available (Manson et al., 2020), can be directly beneficial to the transboundary management of aquifers. Well managed water sources on the domestic level can result in (1) more data for the transboundary agenda and (2) a lower likelihood of Malawi contributing to depleting groundwater levels and aquifer contamination on a transboundary scale. The asset management program facilitated through the Climate Justice Fund: Water Futures Programme could have advantageous outcomes for transboundary aquifer management through providing a basis for long-term strategic management for the WASH sector infrastructure in Malawi (Kalin et al., 2019). Furthermore, the hotspot risk analysis of Malawi's transboundary aquifers presented in chapter 6 of this thesis can additionally go a long way to assisting with domestic water management. A whole-country approach to vulnerability assessment would arguably enable better prioritisation for the Malawian government in terms of addressing individual points or areas of vulnerability. Thus, even if transboundary management isn't a priority for the Malawian government, the transboundary agenda could benefit regardless by the improvement of domestic water management and the achievement of other targets within Sustainable Development Goal 6. The same can be said for other indirect benefits of achieving other goals under the SDGs such as Goal 4 (quality education), Goal 5 (gender equality), Goal 11 (sustainable cities and communities) and Goal 13 (climate action), however these linkages require further investigation (UN Water, 2016).

8.3.4 Recommendations for Future Practice

In addition to the key points from the discussion in 8.3, a series of recommendations for future practice have been developed that are applicable within the wider international context and not just specifically Malawi.

1. Transboundary aquifer assessments and management must become the norm, as it is with their surface water counterparts. In order to be successful, individual countries must take ownership their own transboundary responsibility. Chapter 6 in this thesis in particular, illustrated that it is possible for a country to assess their own transboundary impact through domestic hotspot mapping. Encouraging countries to conduct border based transboundary aquifer assessments, taking this data, and then approaching neighbouring countries to collaborate could be a way to move forward. Similarly, increasing awareness in general of the importance of transboundary resources, how much we rely upon them, and how vulnerable they are can assist in raising transboundary aquifer management in the agenda of governments and international organizations. In 2022, World Water Day will

showcase groundwater and this will be the theme for the annual World Water Development Report (IGRAC, 2020b). Utilizing this increase in momentum and attention on groundwater in order to push the transboundary aquifer agenda will be valuable.

2. Historically, organizations such as IGRAC and UNESCO-IHP have largely implemented and promoted regional and large scale transboundary aquifer assessments. Recognition of the importance of national and locally significant transboundary aquifers could go a long way in promoting local and national scale TBA assessments and management. Similarly, recent transboundary aquifer projects within the international transboundary aquifer community have focused on the understanding and management of single transboundary aquifer systems. The selection of which transboundary aquifers receive such attention and funding is often ambiguous. Directing resources to transboundary aquifers most in need (for example, those identified through a hotspot analysis) would be a more effective approach.

3. Given the recent reporting on SGD 6.5.2 and the predicted failure of the target by 2030, it is hoped that the target indicator methodology will be reassessed. Although the indicator is reported as a proportion of transboundary basin area with an operational arrangement for water cooperation, data on arrangements governing individual transboundary aquifers is also collected. Extracting and analysing this data to present the current level of cooperation globally per transboundary aquifer could allow for a greater understanding of how many transboundary aquifers specifically have agreements or arrangements governing, where they reside globally, alongside highlighting common themes between said aquifers. This could provide useful guidance and exemplar cases for other countries looking to foster cooperative management over their own transboundary aquifers through an agreement or arrangement. This analysis could also highlight transboundary aquifers that aren't governed by operational arrangements but do meet at least 1 of the 4

criteria in order to provide a more realistic view of transboundary cooperation that doesn't necessarily meet the strict 'operational' criteria.

4. Finally, science should always inform law and policy. As scientists within the transboundary aquifer field, we need to learn how to better communicate the complexity of transboundary aquifer systems. We must engage with policy makers in order to ensure this complex science is relayed effectively in legal instruments and policy at all scales. In order to do so, capacity building and engaging in science communication ('sci-com') will be vital. Establishing cooperation through technical agreements first is often…

8.3.5 Recommendations for Future Research

In support of furthering the research first developed in this thesis, a series of recommendation have been made for future scientific research within the field. It is recommended that throughout any further research, the Malawian Government are continually engaged for maximum impact and usefulness.

1. Chapter 5 of this thesis presented a hotspot analysis of transboundary aquifers within Malawi. By extending this analysis across the border into neighbouring Mozambique, Zambia and Tanzania, a greater understanding of potential transboundary risks could be gained. Hotspots identified in Malawi may not be hotspots in neighbouring countries and vice versa. This will ultimately affect how the resources are managed. A step further would be to apply a hotspot analysis across the entirety of the SADC in order to prioritise aquifers for more directed management across the region. SADC-GMI could work closely with member countries to implement transboundary aquifer governance in key transboundary hotspots of concern.

2. This thesis assessed in detail 1 of the 14 transboundary aquifer hotspots identified within its assessment (the Ruo Transboundary System, chapter 7). 13 other hotspots remain, at both the local and national level. The next step for the Malawian Government would be to start to assess these other

hotspots to determine if there is the potential for transboundary groundwater flow in these areas and to determine if the identified risk in this thesis warrants immediate action.

3. Conjunctive management of surface water and groundwater is a key component of IWRM and essential for holistic transboundary aquifer management as often, transboundary aquifers are in some way hydraulically linked to other water sources (e.g. rivers, lakes, precipitation). Moving forward with transboundary aquifer assessments in Malawi and the SADC region, an effort should be made to identify key hydraulic linkages between groundwater and surface waters. Transboundary aquifer legislation and/or agreements adopted within the region should include a conjunctive management component and institutional governance and frameworks should promote and support it wherever possible.

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University of Strathclyde Glasgow

GENERAL RISK ASSESSMENT FORM (S20)

Persons who undertake risk assessments must have a level of competence commensurate with the significance of the risks they are assessing. It is the responsibility of each Head of Department or Director of Service to ensure that all staff are adequately trained in the techniques of risk assessment. The University document “Guidance on Carrying Out Risk Assessments” will be available, in due course, to remind assessors of the current practice used by the University. However, reading the aforementioned document will not be a substitute for suitable training.

Prior to the commencement of any work involving non-trivial hazards, a suitable and sufficient assessment of risks should be made and where necessary, effective measures taken to control those risks.

Individuals working under this risk assessment have a legal responsibility to ensure they follow the control measures stipulated to safeguard the health and safety of themselves and others.

SECTION 1

1.1 OPERATION / ACTIVITY	Complete the relevant details of the activity being assessed.		
Title:	Malawi and Mozambique Fieldwork: General Project Work		
Department:	Civil and Environmental Engineering		
Location(s) of work:	Blantyre urban area, Mulanje (Mozambique) and Milange (Mozambique)	**Ref No.**	001
Brief description: Malawi-based research fieldwork duration April 2019. Field work will be undertaken in Mulanje (Malawi) and Milange (Mozambique), with office and main accomodation in Blantyre City			

1.2 PERSON RESPONSIBLE FOR MANAGING THIS WORK			
Name:	Robert Kalin	**Position:**	PI/Professor
Signature:		**Date:**	XX/04/2019
Department:	Civil and Environmental Engineering		

1.3 PERSON CONDUCTING THIS ASSESSMENT			
Name:	Christina Fraser	**Signature:**	
Name:		**Signature:**	
Name:		**Signature:**	
Date risk assessment undertaken:	10/04/2019		

1.4 ASSESSMENT REVIEW HISTORY

This assessment should be reviewed immediately if there is any reason to suppose that the original assessment is no longer valid. Otherwise, the assessment should be reviewed annually. The responsible person must ensure that this risk assessment remains valid.

	Review 1	**Review 2**	**Review 3**	**Review 4**
Due date:				
Date conducted:				
Conducted by:				

SECTION 2

Work Task Identification and Evaluation of Associated Risks			Page of	Ref No.					
Component Task / Situation	**Hazards Identified**	**Hazard Ref No.**	**Who Might be Harmed and How?**	**Existing Risk Control Measures (RCM)**	**Likelihood**	**Severity**	**Risk Rating**	**Risk L, M, H, VH**	**RCM's Acceptable Y/N**
Pre-departure Planning	N/A	0	N/A	All incidents and near misses must be recorded and reported to Programme Management within 24 hours of occurence. These will be reviewed on a weekly basis by team and used to inform future risk assessments and mitigation measures. Near miss and incident reporting templates will be provided to the group prior to travel	Organised before departure				
Pre-departure Planning	N/A	0a	N/A	Travellers must check the UK FCO website a week before departure for information on security, medical and social issues which may create increased risk (https://www.gov.uk/foreign-travel-advice) Travellers should also register with the University of Strathclyde's Security Assistance Partner UMAL, and check their website for up to date travel information (https://www.drum-cussac.net/)	Organised before departure				
Pre-departure Planning	N/A	1	N/A	All travellers must register for Travel Insurance at http://www.strath.ac.uk/finance/accountingservices/conly/travelinsurance/	Organised before departure				
Pre-departure Planning	Response to emergency: general	2	Travellers may sustain injury, harm or death.	All travellers must carry a mobile phone (with battery and credit) at all times. Travellers must have contact details of all CJF staff and partner organisations saved in their phones. All must carry first aid kit in vehicle while travelling. All must know a route to the nearest hospital is at all times	Organised before departure				
Pre-departure Planning	Disease Prevention: General	3	Travellers may sustain illness.	All travellers advised to obtain relevant vaccinations from GP or travel clinic at least 6 weeks in advance of travel	Organised before departure				
Pre-departure Planning	Malaria Prevention	4	Travellers may contract malaria	All travellers advised to obtain Malaria prevention medication in advance of travel. All travellers should	Organised before departure				

				and advice from their GP or travel clinic to ensure they understand risks of Malaria					
Pre-departure Planning	Forgotten or insufficient supply of medication	5	Travellers medical condition deteriorates owning to lack of medication	All travellers with pre-existing medical conditions to check with GP in advance of travel to discuss how the trip might affect them, ensure sufficient prescription medication for the duration of the trip and obtain letter from GP if necessary. Travellers with notable medical condition must make staff and supervisors aware of this before travelling.	Organised before departure				
Pre-departure Planning	Medication Supply	5b	Travellers do not have sufficient medical supplies	Travellers with medical conditions which require medication (including asthma), must carry sufficient spare medication. While travelling this should be stored in at least three different locations (e.g. on person, in vehicle, in bag) in case of loss of one batch	Organised before departure				
Pre-departure Planning	Safety call procedure	6	Travellers may become lost/ injured while working.	Travellers will follow programmed safety check procedure, including safety calls for travelling in exceptional or unplanned circumstances	Organised before departure				
Pre-departure Planning	Driving safety procedure	7	Travellers may sustain serious injury or die if involved in road traffic accident	Travellers will follow programmed driving procedure, including additional measures for long-distance driving (journey plan, safety calls, planned breaks, no driving in dark). No students will drive vehicles in Mozambique during research work.	Organised before departure				
Flights to Malawi	Deep vein thrombosis	8	Travellers: DVT	Move around and stretch during long flights	1	3	3	L	Y
Driving in Mozambique	Car accident: poor quality roads and poor driving standards	9	Drivers, passengers and pedestrians: injury	Vehicles only to be driven by experienced Malawian driver- no students to drive, all driving must finish before dark, plan route, follow road rules, drive to conditions, avoid fatigue, check vehicle safety features, wear seatbelt, have phone and communications,	3	4	12	H	N
Driving in Mozambique	Car accident: long journey	10	Drivers, passengers and pedestrians: injury	In addition to above, follow programmed safety measures for long journeys, over 2 hours (planned route and arrival time, safety call before departure and upon arrival)	3	3	9	M	Y
Driving in Mozambique	Car accident: driving in unfamiliar conditions	11	Drivers, passengers and pedestrians: injury	Vehicles only to be driven by experienced Malawi driver- no students to drive, all driving must finish before dark, plan route, follow road rules, drive to conditions, avoid fatigue, check vehicle safety features, wear seatbelt, have phone and communications,	3	4	12	H	N

Driving in Mozambique	Car becoming stuck (flood, mud, rivers etc) or lost from route	12	Drivers, passengers and pedestrians: becoming stranded	Vehicles only to be driven by experienced Mozambiquean driver- no students to drive, all driving must finish before dark, plan route, follow road rules, drive to conditions, avoid fatigue, check vehicle safety features, wear seatbelt, have phone and communications,, avoid known obstacles (rivers), have GPS/ phone, check weather, avoid night driving, safety call upon arrival	3	2	6	M	Y
Driving in Mozambique	Car breakdown	13	Drivers, passengers and pedestrians: becoming stranded/injury	Check vehicle maintainance and state of repair before leaving, journey plan/ safety call to confirm arrival	3	2	6	M	Y
City: Road Safety	Becoming injured as a pedestrian – significant risk in built up areas (i.e. Blantyre City)	14	Pedestrians, all working around roads	Use established road safety measures (stop, look, listen), cross roads at designated places, stay away from busy road junctions, take taxi or minibus if long journey required	3	3	9	M	Y
City: Walking around	Attack and/or theft	15	All on streets	Avoid walking alone in city, no walking at night (take taxi instead), stay in groups, avoid known areas of danger (close to bars or alcohol spots), do not take valuables out into town, avoid showing valuables (i.e. phone, money) off	3	3	9	M	Y
City: Accommodation Security	Break ins or theft of personal belongings.	16	Travellers may become anxious or sustain physical injury	Do not invite unknown or not trusted persons into accomodation, keep doors locked, keep valuables locked up. Kabula Lodge has guards, gates and barred windows	3	3	9	M	Y
City: Working in Buildings	Insufficient or poorly maintained fire escape routes, lack of fire warning system.	17	Travellers may sustain burns or smoke inhalation or fatal injuries.	Mozambique has limited fire safety control measures in place, remain aware of escape routes, avoid entering buildings suspected to be unsafe	3	3	9	M	Y
Civil Unrest	Caught up in political demonstrations or civil unrest	18	Travellers may suffer verbal or physical abuse	All will regualry check FCO (https://www.gov.uk/foreign-travel-advice/Mozambique/safety-and-security) and UMAL (https://www.drum-cussac.net/) websites for travel advice/alerts in advance of travel and during trip. Information on travel security, local customs, entry requirements, health etc. will be provided during briefing sessions, Mozambique based staff will inform group of any possible civil unrest and review situation on a daily basis	3	4	12	H	N
General activities in Mozambique	Trip & fall hazards	19	All: injury	Keep work and living areas tidy, first aid kit, know nearest hospital/ treatment centre, wear PPE for relevant tasks	4	1	4	M	Y

General activities in Mozambique	Burns and similar	20	All: injury	Take care operating cooking appliances, first aid kit, know nearest hospital/ treatment centre	3	2	6	L	Y
General activities in Mozambique	Cuts, scrapes, etc	21	All: injury	First aid kit, know nearest hospital/ treatment centre	3	2	6	M	Y
General activities in Mozambique	Sunburn, heat exhaustion	22	All: injury and illness	Stay out of sun, wear hats, wear suncream, drink lots of water	3	3	9	M	Y
General activities in Mozambique	Animals	23	All: injury and illness from animal bites	Keep away from animals, first aid kit, appropriate clothing, know nearest hospital/ treatment centre	2	3	6	M	Y
General activities in Mozambique	Insects and spiders	24	All: injury/ illness from bites, malaria, fleas	Insect repellent, nets while sleeping, appropriate clothing to cover skin, know nearest hospital/ treatment centre	2	4	8	M	Y
General activities in Mozambique	Insects: Mosquitos	25	All: injury/ illness from bites, malaria, fleas	Insect repellent, nets while sleeping, appropriate clothing to cover exposed skin, anti-malarials, know nearest hospital/ treatment centre	2	4	8	M	Y
General activities in Mozambique	Food/drink	26	All: illness i.e. food poisoning	Wash hands + hygiene, avoid food that has been left out/ reheated, use purification tablets as appropriate	3	3	9	M	Y
General activities in Mozambique	General tropical/ water borne diseases not present in UK	27	All: illness i.e. cholera	Wash hands, avoid stagnant water, good hygiene, know location of treatment centre, avoid eating uncooked food soaked or washed in water	2	4	8	M	Y
General activities in Mozambique	Tropical Disease: Schistosomiasis	28	All: Serious illness	Avoid water suspected to be contaminated with Schistosomiasis, if in contact follow treatment testing as advised by medical professional	2	4	8	M	Y
General activities in Mozambique	Sexually transmitted infections	29	All: illness esp HIV	Awareness and understanding of HIV infection and associated risks, avoid contact with infection	1	5	5	M	Y
General activities in Mozambique	Extreme Weather	30	All: injury	Plan journeys taking into account possible extreme weather. i.e. floods, rains, wind (esp relevant in Mozambique rainy season December to April). Check weeather forecast, speak to local people to understand localised risks, use GPS to track location, plan alternative routes home	3	4	12	H	N
Pre fieldwork planning	Dangerous weather (i.e. flooding, heavy rainfall, wind, lightening)	31	Attendees may sustain injury	Before departing for fieldwork the team must check weather forecast for the work area, if heavy rainfall or storms are possible the work can be cancelled / delayed to avoid dangerous weather	2	4	8	M	Y
Pre fieldwork planning	All workers must have required PPE and equipment before commencing fieldwork	32	Attendees may sustain injury	Before departing for fieldwork the team must check that all workers have the required PPE, and suitable shoes / clothing for the works required	2	3	6	M	Y
Pre fieldwork planning	Attendees could have pre-existing medical issue which could cause difficulties in field demonstration	33	Attendees may become unwell or sick	Before departing for fieldwork the team must check to see if any workers have pre-existing medical conditions or medical requirements that may add complications to completing works safely	1	5	5	M	Y

Field work	Manual Work: Trips and falls	34	All: injury	Demarcate working area, keep site in good order, remove any obstacles and sharp edges, PPE worn at all times, first aid kit available	3	3	9	M	Y
Field work	Manual work: back injury (or similar)	35	All: injury	Make sure all equipment is in good working order, make sure correcct tool is being used for each task,, Follow good lifting practice, plan lifting and moving of heavy items, share workloads, PPE	3	3	9	M	Y
Field work	Manual Work: Impact injury	36	All: injury	Make sure all equipment is in good working order, make sure correcct tool is being used for each task,, wear PPE at all times, plan all equipment lifting and moving, keep work area tidy, store equipment and parts in appropriate place, people not directly working must be outside demarcated work area, first aid kit available	3	3	9	M	Y
Field work	Manual Handling above head height	37	All: injury	Plan lifting tasks before commencing, wear appropriate PPE, share workload, follow established manual handling procedures	3	3	9	M	Y
Field work	Contaminated / poisonous materials	38	All: illness/injury from hazardous materials	Remove all haz waste from site, store haz materials correctly, PPE, first aid kit, follow established COSHH process for materials safety	2	4	8	M	Y
Field work	Handling Fuel	39	All: fire and associated injuries / equipment damage	Fuel to be stored in an appropriate sealed container, fuel to be kept out of sunlight and away from sources of ignition, fuel only handled Strathclyde Staff, follow established COSHH process for materials safety	1	5	5	M	Y
Field work	Handling hazardous materials (chlorine, solvent cement)	40	All: Injury, Toxic, Burns etc	Store hazardous materials appropriately, wear appropriate PPE (i.e. gloves, goggles)	2	3	6	M	Y
Field work	Sunburn, heat exhaustion	41	All: injury and illness	Stay out of sun, wear hats, wear suncream, drink lots of water	3	3	9	M	Y
Field work	Becoming lost	42	All: becoming stranded	Don't work alone, plan moving between sites, use GPS, have radio/ phone as needed	2	4	8	M	Y
Field work	Vehicles in work area	43	All: injury from vehicle incident	Vehicles must be parked in a dedicated safe area away from works, vehicles will not be driven close to or within the working area	3	4	12	H	N
Field work	Heavy machinery operating in work area	44	All: injury	Stay away from machinery, demarcate machine working areas and safe distances, good site layout, PPE (overalls, hard hat, boots, goggles, gloves, etc), stay aware, do not enter machine working area until safe	3	4	12	H	N
Field work	Weather (lightening)	45	All: injury	If a lightning storm develops in the working area, works should stop and staff should shelter in a safe place until the storm has passed	2	4	8	M	Y

Field work	Border crossings/legal entry	46	Travellers may have issues at the border	Ensure visa's are obtained, speak to border control on crossing and arrive back at the border within good time	2	4	8	M	Y
Field work	Language barrier	47	Travellers may not be able to communicate their work efectively	Ensure Portuguese speaker accompanies the travellers when going into Mozambique	2	4	8	M	Y
Field work	Unknown conditions	48	Travellers not been to field area in Moz. before	Conduct a renaissance survey of the field area before field sampling begins. Ensure mobile date works and is available in case needed.	2	4	8	M	Y
Field work	Contact with WDO/equivalent	49	Contact with Moz WDO may be difficult	As soon as border crossed on renaissance survey, drive to Milange village to find WDO. Portuguese speaker should be able to assist.	2	4	8	M	Y
Field work	Arrest/issues with local authority	50	Arrest risk if proper documentation not obtained	Ensure visas are obtained, speak to border control on crossing, ensure written permission obtained before sampling and conduct initial visit to brief everyone	2	4	8	M	Y
Field work	Community confusion/unrest	51	Risk of unrest	Ensure communities are pre-briefed and take a local who can speak the language with us sampling	2	4	8	M	Y
Field work	National Level permission	52	Risk of arrest	Ensure to obtain written permission both sides of the border	2	4	8	M	Y
Field work	Stranded in Mozambique	53	Risk of border issues	Do not go too far from the border and return within good time	2	4	8	M	Y
Field work	Sampling in Mozambique	54	Risk of community confusion and/or unrest	Ensure permission is obtained before sampling and communities briefed.	2	4	8	M	Y

SECTION 3

Identified Actions to Improve Control of Unacceptable Risks (as evaluated in Section 2) **Page of Ref No.**

Hazard Ref No.	Risk	Recommended Additional Risk Control Measures	Implemented Y/N	Action By	Target Date	Completion Date	Revised Risk				Revision of Risk Signed Off
							Likelihood	Severity	Risk Rating	Risk L, M, H	
9	H	Car accident: for journeys of long duration (>2 hours) or to new or exceptional areas, a journey plan must be made and shared with the Programme Manager prior to leaving (this journey plan should include: map, planned stops, planned safety calls, vehicle inspection etc), safety	Y	Travellers			2	4	8	M	

		checks must be made with group leader before departure and after arrival									
18	H	Civil Unrest: if persistent unrest is occurring inside work areas, all field work must be postponed until the unrest has passed. Works can re-commence when safety status has been reviewed by the Programme Manager and Mozambiquean (Government and NGO) staff and deemed to be low risk	Y	Travellers			2	4	8	M	
30	H	Extreme Weather: If extreme weather predictions for CJF working areas are being made (particularly wrt flooding) fieldwork should be cancelled until all warnings have passed	Y	Travellers			2	4	8	M	
44	H	Vehicles in work area: if working around vehicles, travellers must designate a ‘safe working’ area which clearly separates vehicle moving area from working area (using safety tape or similar). Vehicles must not enter the safe working area	Y	Travellers			2	4	8	M	
45	H	Heavy machinery operating in work area: if working around heavy machinery a designated ‘machine working’ area must be cordoned off, workers must not enter the machine working area unless the machine has been made safe and the operator is aware of all workers	Y	Travellers			2	4	8	M	

SECTION 4

RECORD OF SIGNIFICANT FINDINGS	**Page of** **Ref No.**

Where this Section is to be given to staff etc., without Sections 2 & 3, please attach to the front of this page, a copy of the relevant Section 1 details.

The significant findings of the risk assessment should include details of the following:

- The identified hazards
- Groups of persons who may be affected
- An evaluation of the risks
- The precautions that are in place (or should be taken) with comments on their effectiveness
- Identified actions to improve control of risks, where necessary

Alternatively, where the work activity/procedure is complex or hazardous, then a written Safe System of Work (SSOW) or Standard Operating Procedure (SOP) is advised that should incorporate the significant findings. Such documents should again, have the relevant Section 1 attached. Please state below whether either a SSOW or SOP is available in this case.

Relevant SSOW available	Yes ☐	No ☐	Relevant SOP available	Yes ☐	No ☐

Significant Findings: (Please use additional pages if further space is required)

All incidents and near misses must be recorded and reported to Programme Management within 24 hours of occurence. These will be reviewed on a weekly basis by team and used to inform future risk assessments and mitigation measures.

Main hazards:

- Road accidents - minimised by good driving practice and journey planning
- Becoming lost/stranded - minimised by good journey planning, good communications (phone or radio), using GPS and maps
- Malaria - minimised by mosquito nets and taking anti-malarial
- Other tropical/ water-borne diseases - minimised by good hygiene and avoiding sources of illness
- Food poisoning - minimised by good hygiene, and knowing quality and source of food
- Sun exposure/ heat stroke - minimised by keeping out of sun, wearing sun-cream, hats etc
- Heavy vehicles/ machinery on site - minimised by good communication with operators, good awareness, demarcating safe distances from machinery

When undertaking borehole and handpump surveys, a perimeter must be demarcated around the active site working area (i.e. luminous tape). Only approved work persons allowed in work area, all working persons must wear appropriate PPE.

Appropriate PPE is to be worn at all times when on site.

- For borehole forensics work, all working persons must wear boots, hi-vis vest and hard-hat
- Steel toe safety boots: when heavy lifting + heavy tools
- Gloves: when using tools, or handling hazardous substances
- Safety glasses: when using tools, or handling hazardous substances

Travel insurance must be arranged through the University of Strathclyde by all travellers.

In August to October 2017 there were a number of incidents of violence and unrest in the eastern part of the Southern Region of Mozambique, associated with ‘Bloodsucker’ rumours. As of 12 December 2017, no incidents have been reported, however travellers are urged to take caution and check status of unrest if travelling or working in districts: Mulanje, Phalombe, Thyolo, Chiradzulu

In March 2019 Mozambique and Malawi was hit by extreme weather resulting in extensive flooding in the south of the country. Field area is currently not flooded however travellers are urged to still be careful and regularly check weather updates.

SECTION 5

RECEIPT OF SIGNIFICANT FINDINGS OF RISK ASSESSMENT **Page of**

Please copy this page if further space is required. **Ref No.**

All individuals working to the risk assessment with the Ref. No. as shown, must sign and date this Section to acknowledge that they have read the relevant risk assessment and are aware of its contents, plus the measures taken (or to be taken by them) to safeguard their health and safety and that of others.

If following review of the assessment revisions are minor, signatories may initial these where they occur in the documentation, to indicate they are aware of the changes made. If revisions are major, it is advisable to produce a new risk assessment and signature page.

NAME (Print)	SIGNATURE	DATE
Christina Fraser	C.Fraser	10/04/2019

Appendix B, Stratigraphic Column of Geological Units

Lithology Type	Malawi	Mozambique	Zambia	Tanzania
Superficial Deposits	River alluvium	Clayey alluvium including sand layers	-	Alluvium
	Colluvium and residual soils	Sandy alluvium including gravel, silt and clay layers		Lacustrine deposits
Karoo Supergroup	Basalt lava flows	Upper amygdaloidal basalt	-	-
	Upper sandstones: grits and sandstones	Compact siliceous sandstones of Upper Karoo	-	-
	Mwanza grits and shales	Conglomerate and gritty arkose	-	Conglomerate, sandstones, siltstones, mudstones, shales
	Lower sandstones: grits and sandstones	Conglomerate, sandstone and schist	-	-
	Mwanza gritty conglomerates	Gritty conglomerates	-	-
Basement Complex	Granite	Granite	Granite	-
	Dzalanyama granite	-	Undifferentiated granite and gneiss	Biotite gneiss
	Biotite-nepheline-gneiss and nepheline-syenite	Nepheline syenite	-	-

	Perthite gneiss grading into pethosite and perthite syenite	Syenite and monzonite/syenite and mangerite	-	-
	Perthite gneiss and perthitic syenite	Syenite and mangerite	-	-
	Quartzofeldspathic granulite and quartzite	High grade gneiss with minor granulite	-	-
	Migmatite	-	Granulite	-
	Biotite gneiss with garnet	-	Undifferentiated granite and gneiss	-
	Semi-pelitic hornblende biotite gneiss	High grade gneiss	Undifferentiated granite and gneiss	-
	Hornblende biotite gneiss	Gneiss migmatite	-	-
	Biotite gneiss with amphibolite dykes	-	Granite	Biotite gneiss
	Hornblende pyroxene gneiss	High grade gneiss, granulite in places/gneiss migmatite	-	-
	Sillimanite-cordierite-garnet gneiss	-	Undifferentiated granite and gneiss	-
	Charnockitic gneiss and granulite	High grade gneiss/granulitic gneiss/with amphibolite and piroxenite	-	-

Appendix C, Summary of Transboundary Aquifer Hotspot Descriptions

Summary of Transboundary Aquifer Hotspot Descriptions

National

Transboundary aquifer 1 (figure 3) is a two layered system composed of charnockitic gneiss and granulite lithology overlaid by unconsolidated colluvium. It is a weathered basement aquifer that stores and transmits groundwater through secondary saprolitic porosity (Smith-Carrington and Chilton, 1983 in Fraser et al., 2020b). This aquifer had low borehole yields, a transmissivity of between 5-35 m^2/day and a hydraulic conductivity of 0.5-1.5m m/d. Groundwater within this aquifer is flowing from Mozambique into Malawi in its northern extent, and from Malawi to Mozambique in its southern extent. This basement aquifer is overlaid by another superficial aquifer unit composed of colluvium and residual soils. Is it suspected although unproven that these two aquifers are hydraulically connected. The superficial aquifer is highly productive, with a transmissivity of 50-300 m^2/day and a hydraulic conductivity of 1-10m/d (Smith-Carington and Chilton, 1983; Habgood, 1964; Bradford, 1973 in Fraser at al, 2018).

Transboundary aquifer 2 (figure 3) is composed of charnockitic gneiss and granulite lithology. It is a fractured basement aquifer that stores and transmits groundwater through secondary fractures within the rock, formed during the East Africa Rift System development. This aquifer had low borehole yields, a transmissivity of between 5-35 m^2/day and a hydraulic conductivity of 0.5-1.5m m/d. (Chilton and Smith-Carington, 1984 and Habgood, 1964 in Fraser et al., 2020b). Groundwater within this aquifer is flowing from Malawi into Mozambique.

Transboundary aquifer 3 (figure 3) is composed of biotite-gneiss lithology with garnet in parts. It is a weathered basement aquifer that stores and transmits groundwater through secondary saprolitic porosity (Smith-Carrington and Chilton, 1983 in Fraser t al, 2020b). This aquifer had low borehole yields, a transmissivity of between 5-35

m^2/day and a hydraulic conductivity of 0.5-1.5m m/d. (Chilton and Smith-Carington, 1984 and Habgood, 1964 in Fraser et al., 2020b). Groundwater within this aquifer is flowing from Zambia to Malawi. This basement aquifer is overlaid by another superficial aquifer unit composed of colluvium and residual soils. Is it suspected although unproven that these two aquifers are hydraulically connected. The superficial aquifer is highly productive, with a transmissivity of 50-300 m^2/day and a hydraulic conductivity of 1-10m/d.

Local

Transboundary aquifer 4 (figure 4) is composed of colluvium and residual soils. The aquifer is highly productive and unconfined, with a transmissivity of 50-300 m^2/day and a hydraulic conductivity of 1-10m/d. Water table depth range from 5-10m. This aquifer is potentially connected to a fractured basement aquifer below, although there is no data to support this. Groundwater within this aquifer is flowing from Mozambique to Malawi (Smith-Carington and Chilton, 1983; Habgood, 1964; Bradford, 1973 in Fraser at al., 2018).

Transboundary aquifer 5 (figure 4) is composed of perthite gneiss grading into perthosite and perthitic syenite lithology. It is a fractured basement aquifer that stores and transmits groundwater through secondary fractures within the rock, formed during the East Africa Rift System development. This aquifer had low borehole yields, a transmissivity of between 5-35 m^2/day and a hydraulic conductivity of 0.5-1.5m m/d. (Chilton and Smith-Carington, 1984 and Habgood, 1964 in Fraser et al., 2020b). Groundwater within this aquifer is flowing from Mozambique to Malawi.

Transboundary aquifer 6 (figure 4) is composed of hornblende-pyroxene-gneiss lithology. It is a weathered basement aquifer that stores and transmits groundwater through secondary saprolitic porosity (Smith-Carrington and Chilton, 1983 in Fraser et al., 2020b). This aquifer had low borehole yields, a transmissivity of between 5-35 m^2/day and a hydraulic conductivity of 0.5-1.5m m/d. (Chilton and Smith-Carington, 1984 and Habgood, 1964 in Fraser et al., 2020b). Groundwater within this aquifer is flowing from Malawi to Mozambique.

Transboundary 7 (figure 4) is composed of hornblende-pyroxene-gneiss lithology. It is a fractured basement aquifer that stores and transmits groundwater through secondary fractures within the rock, formed during the East Africa Rift System development. This aquifer had low borehole yields, a transmissivity of between 5-35 m^2/day and a hydraulic conductivity of 0.5-1.5m m/d. (Chilton and Smith-Carington, 1984 and Habgood, 1964 in Fraser et al., 2020b). Groundwater within this aquifer is flowing from Malawi to Mozambique.

Transboundary aquifer 8 (figure 4) is composed of Quartzofeldspathic granulite and quartzite lithology. It is a fractured basement aquifer that stores and transmits groundwater through secondary fractures within the rock, formed during the East Africa Rift System development. This aquifer had low borehole yields, a transmissivity of between 5-35 m^2/day and a hydraulic conductivity of 0.5-1.5m m/d. (Chilton and Smith-Carington, 1984 and Habgood, 1964 in Fraser et al., 2020b). Groundwater within this aquifer is flowing from Mozambique to Malawi.

Transboundary aquifer 9 (figure 4) is composed of perthite-gneiss and perthitic syenite lithology. It is a weathered basement aquifer that stores and transmits groundwater through secondary saprolitic porosity (Smith-Carrington and Chilton, 1983 in Fraser et al., 2020b). This aquifer had low borehole yields, a transmissivity of between 5-35 m^2/day and a hydraulic conductivity of 0.5-1.5m m/d. (Chilton and Smith-Carington, 1984 and Habgood, 1964 in Fraser et al., 2020b). Groundwater within this aquifer is flowing from Mozambique to Malawi.

Transboundary aquifer 10 (figure 4) is composed of Charnockitic gneiss and granulite lithology. It is a fractured basement aquifer that stores and transmits groundwater through secondary fractures within the rock, formed during the East Africa Rift System development. This aquifer had low borehole yields, a transmissivity of between 5-35 m^2/day and a hydraulic conductivity of 0.5-1.5m m/d. (Chilton and

Smith-Carington, 1984 and Habgood, 1964 in Fraser et al., 2020b). Groundwater within this aquifer is flowing from Mozambique to Malawi

Transboundary aquifer 11 (figure 4) is composed of silimanite-cordierite-garnet gneiss lithology. It is a fractured basement aquifer that stores and transmits groundwater through secondary fractures within the rock, formed during the East Africa Rift System development. This aquifer had low borehole yields, a transmissivity of between 5-35 m^2/day and a hydraulic conductivity of 0.5-1.5m m/d. (Chilton and Smith-Carington, 1984 and Habgood, 1964 in Fraser et al., 2020b). Groundwater within this aquifer is flowing from Zambia to Malawi.

Transboundary aquifer 12 (figure 4) is composed of Migmatite lithology. It is a weathered basement aquifer that stores and transmits groundwater through secondary saprolitic porosity (Smith-Carrington and Chilton, 1983 in Fraser et al., 2020b). This aquifer had low borehole yields, a transmissivity of between 5-35 m^2/day and a hydraulic conductivity of 0.5-1.5m m/d. (Chilton and Smith-Carington, 1984 and Habgood, 1964 in Fraser et al., 2020b). Groundwater within this aquifer is flowing from Zambia to Malawi.

Transboundary aquifer 13 (figure 4) is composed of biotite gneiss with amphibiotite dykes. It is a weathered basement aquifer that stores and transmits groundwater through secondary saprolitic porosity (Smith-Carrington and Chilton, 1983 in Fraser et al., 2020b). This aquifer had low borehole yields, a transmissivity of between 5-35 m^2/day and a hydraulic conductivity of 0.5-1.5m m/d. (Chilton and Smith-Carington, 1984 and Habgood, 1964 in Fraser et al., 2020b). Groundwater within this aquifer is flowing from Zambia to Malawi.

Transboundary aquifer 14 (figure 4) is composed of River alluvium lithology. The aquifer is highly productive and unconfined, with a transmissivity of 50-300 m^2/day and a hydraulic conductivity of 1-10m/d. Water table depth range from 5-10m. This aquifer is potentially connected to a fractured basement aquifer below, although there is no data to support this. Groundwater within this aquifer is flowing from

Mozambique to Malawi (Smith-Carington and Chilton, 1983; Habgood, 1964; Bradford, 1973 in Fraser at al., 2018). Groundwater within this aquifer is flowing from Malawi to Tanzania.

Appendix D, Raw Geochemical and isotopic Data

STATION ID	STATION NAME	STATION LOCATION	T/A	DISTRICT	SAMPLE DATE	SOURCE	EASTING	NORTHING	ALTITUDE	δ2H, ‰	δ18O, ‰	D-Excess
MW01	Muloza River	M2 Road Bridge	Mabuka	Mulanje	2019/04/11	RIVER	769597	8225453	639	-38,9	-6,92	16,5
MW02	Mikundi Village Borehole	Mikundi Village Borehole	Mabuka	Mulanje	2019/04/11	BH	769597	8225453	-	-26,3	-4,93	13,1
MW03	Changoni Primary School Borehole	Mlofinyo Village	Mabuka	Mulanje	2019/04/11	BH	774068	8222703	637	-23,7	-4,47	12,1
MW04	Chanunkha River	M2 Road Bridge	Mabuka	Mulanje	2019/04/11	RIVER	774646	8223207	608	-28,1	-5,43	15,3
MW05	Lichenya River	M2 Road Bridge	Mabuka	Mulanje	2019/04/11	RIVER	776612	8222183	612	-34,6	-6,45	17,0
MW06	Ruo River	M2 Road Bridge	Njema	Mulanje	2019/04/11	RIVER	785657	8220703	622	-26,1	-4,97	13,7
MW07	Sazikani Village Borehole	Sazikani Village Borehole	Mabuka	Mulanje	2019/04/11	BH	775167	8223033	617	-27,3	-5,09	13,4
MW08	Dambula Primary School	Dambula Primary School	Njema	Mulanje	2019/04/12	BH	789159	8220632	663	-24,2	-4,65	13,0
MW09	Makaula Village Borehole	Makaula Village Borehole	Mabuka	Mulanje	2019/04/12	BH	773195	8224393	632	-27,0	-5,63	18,0
MW10	Bona Village Borehole	Bona Village Borehole	Njema	Mulanje	2019/04/17	BH	787725	8224680	654	-25,4	-5,05	15,0
MW11	Kaminyo House Shallow Well	Kaminyo House Shallow Well	Mabuka	Mulanje	2019/04/17	SW	783118	8218762	636	-23,7	-4,76	14,4
MW12	Mimosa Post Office. Borehole	Mimosa Post Office. Borehole	Mabuka	Mulanje	2019/04/17	BH	779736	8220143	656	-26,4	-4,93	13,0
MW13	Duswa Village Boehole	Duswa Village Boehole	Mabuka	Mulanje	2019/04/17	BH	778020	8217825	638	-26,3	-4,78	11,9
MW14	Mathambi Mosque Borehole	Nanyolo Village	Mabuka	Mulanje	2019/04/17	BH	771973	8217708	616	-27,7	-4,94	11,8
MW15	Mizimu Market Borehole	Mose Village	Mabuka	Mulanje	2019/04/18	BH	766211	8218084	592	-29,2	-5,09	11,5
MW16	Khavala Village Borehole	Khavala Village Borehole	Mabuka	Mulanje	2019/04/18	BH	769709	8221166	601	-24,7	-4,62	12,3
MW17	Lichenya River	At the source	Mabuka	Mulanje	2019/04/18	RIVER	778691	8229029	937	-28,8	-5,83	17,8
MW18	Muloza River	At M2 Road Bridge-Muloza Border	Njema	Milanje	2019/04/16	RIVER	792632	8220231	631	-32,8	-5,94	14,7
MZ01	SDA Church	Bauleni Village	Chilinji	Milanje	2019/04/15	BH	766882	8204552	642	-32,4	-5,51	11,7
MZ02	Zalimba Village Borehole	Zalimba Village Borehole	Dashudwa	Milanje	2019/04/15	BH	770668	8202508	660	-30,0	-5,36	12,9
MZ03	Ruo River	M'besa Village	Chilinji	Milanje	2019/04/15	RIVER	772464	8214302	577	-31,0	-5,68	14,4
MZ04	M'besa Primary School Borehole	M'besa Primary School Borehole	Dashudwa	Milanje	2019/04/15	BH	774751	8211951	610	-29,6	-5,10	11,2
MZ05	Chipango Residence	Ngwale Village	Chitsulo	Milanje	2019/04/15	SW	774052	8208677	655	-27,8	-5,04	12,5
MZ06	Vulalo Secondary School	Vulalo Secondary School	Chitsulo	Milanje	2019/04/15	BH	780103	8204738	660	-28,6	-5,05	11,8
MZ07	Ligudula Village Borehole	Ligudula Village Borehole	Chitsulo	Milanje	2019/04/15	BH	781426	8212496	601	-28,6	-5,08	12,0
MZ08	Mulongosi River	At Road Bridge	Chitsulo	Milanje	2019/04/15	RIVER	781351	8212634	586	-31,2	-5,27	11,0
MZ09	Mbidzi Village Borehole	Mbidzi Village Borehole	Nazombe	Milanje	2019/04/16	BH	786348	8216825	647	-27,0	-4,84	11,7
MZ10	Khukhi Residence	Ponderani Village	Ponderani	Milanje	2019/04/16	SW	781783	8213755	625	-29,7	-5,24	12,2
MZ11	N'doda Residence	Luwani Village	Ponderani	Milanje	2019/04/16	SW	783801	8215782	645	-26,5	-4,74	11,4
MZ12	Lihonga Residence	Mbidzi Village	Nazombe	Milanje	2019/04/16	SW	789345	8216503	661	-24,0	-4,45	11,6
MZ13	Yazi River	At Road Bridge in Mbidzi Village	Nazombe	Milanje	2019/04/16	RIVER	790026	8217528	623	-28,1	-5,00	11,9
MZ14	Elumba Hospital Borehole	Milanje Township	Nazombe	Milanje	2019/04/16	BH	792879	8218038	658	-29,1	-5,09	11,6
MZ15	Area 25 June Borehole	Milanje Township	Nazombe	Milanje	2019/04/16	BH	795525	8218747	661	-26,6	-4,99	13,3
MZ16	Fabilika River	At Road Bridge in Nyasombe Village	-	Milanje	2019/04/16	RIVER	796064	8219789	654	-27,2	-5,33	15,4
MZ17	Nyangasale River	Area 14 Road Bridge	-	Milanje	2019/04/16	RIVER	796096	8218788	655	-27,2	-5,34	15,5
MZ18	Liase River	N1 Road Bridge	Mang'anira	Milanje	2019/04/16	RIVER	796861	8216183	657	-26,9	-5,05	13,5

STATION ID	pH	EC, µS/cm	TDS, mg/l	Temp, ^{0} C	TURBIDITY, NTU	CO3, mg/l	HCO3, mg/l	Cl,mg/l	SO4, mg/l	NO3, mg/l	Na, mg/l	K, mg/l	Ca, mg/l	Mg, mg/l	Fe, mg/l	Hardness, mg/l	Alkalinity, mg/l
MW01	7,74	19	9	28,7	52,0	0,0	3	4,3	0,94	0,010	3,2	<0.10	0,9	0,10	0,019	3	2
MW02	8,14	109	54	26,2	5,3	2,0	22	19,3	1,13	1,510	9,8	0,30	10,4	0,23	0,018	27	21
MW03	8,19	35	17	27,2	0,1	1,2	6	5	0,44	0,250	3,5	<0.10	1,80	0,80	0,011	8	7
MW04	7,65	23	11	27,1	80,4	0,0	5	2,6	4,22	0,040	1,7	<0.10	1,9	0,8	0,193	8	4
MW05	6,97	12	6	23,7	12,9	0,0	5	1,5	0,95	1,500	0,8	<0.10	1,6	0,3	0,055	5	4
MW06	8,12	16	8	24,1	21,8	1,0	4	1,6	0,25	0,030	1,0	0,20	1,6	0,40	0,066	6	5
MW07	8,04	110	55	24,2	0,2	1,0	34	19,1	0,04	0,970	10,0	0,70	10,8	2,2	0,007	36	30
MW08	7,83	117	59	31,2	0,2	0,0	35	14,0	6,44	0,220	10,0	0,50	12,0	0,59	0,051	32	29
MW09	7,77	122	61	25,3	1,0	0,0	42	14,0	3,26	0,050	10,0	0,40	8,9	3,81	0,068	38	34
MW10	6,92	26	13	23,9	0,6	0,0	5	2,8	4,2	0,060	2,0	0,10	2,50	0,30	0,018	7	4
MW11	6,98	57	29	25,2	32,7	0,0	18	6,8	0,55	0,330	5,1	<0.10	6,00	0,26	0,015	16	15
MW12	7,75	25	13	26,2	1,7	0,0	6	2,7	2,23	0,040	2,2	<0.10	2,50	0,10	0,005	7	5
MW13	8,20	178	89	26,0	0,2	0,0	74	19,1	2,64	0,170	10,0	0,30	22,4	2,56	0,004	66	61
MW14	7,85	191	96	26,4	0,3	0,0	62	14,0	2,54	0,100	10,5	0,10	20,0	1,10	0,018	54	51
MW15	8,16	209	122	27,5	0,5	2,0	92	16,8	1,15	0,110	11,0	0,20	14,8	10,7	0,026	128	81
MW16	8,08	83	49	27,2	0,1	0,0	15	12,0	10,4	0,130	7,5	<0.10	7,80	0,67	0,011	22	12
MW17	8,24	17	10	23,4	0,6	1,0	5	1,5	0,84	0,010	1,1	<0.10	1,7	0,58	0,03	7	6
MW18	7,11	31	16	28,1	33,6	0,0	10	5,3	1,52	0,100	2,5	0,10	2,8	0,80	0,319	11	8
MZ01	8,27	325	162	26,3	0,1	4,0	180	12,0	1,04	0,120	10,0	1,10	38,6	16,1	0,001	163	154
MZ02	7,75	145	73	26,9	0,1	0,0	56	15,3	0,94	0,010	9,0	1,40	13,8	3,20	0,002	48	46
MZ03	7,43	45	23	28,9	16,6	0,0	13	7,0	0,30	0,050	5,0	0,30	4,0	0,1	0,066	11	10
MZ04	8,44	410	205	27,1	0,2	5,0	198	20,9	3,37	0,080	17,0	0,60	51,0	11,8	0,001	176	171
MZ05	7,89	137	68	27,5	6,2	0,0	50	15,0	2,11	0,040	9,8	1,70	10,0	4,70	0,026	44	41
MZ06	8,05	268	134	28,0	0,2	1,9	120	19,0	2,00	0,060	15,0	1,40	24,0	10,7	0,013	104	102
MZ07	7,87	129	64	27,5	0,5	0,0	49	13,0	3,90	0,090	9,8	1,20	11,0	3,50	0,005	42	40
MZ08	8,20	99	50	27,0	25,1	2,0	18	10,0	8,80	0,100	7,0	<0.10	7,5	2,1	0,081	27	18
MZ09	8,04	242	120	29,4	0,2	1,5	103	18,5	3,40	0,010	10,0	0,50	18,0	11,7	0,011	93	87
MZ10	7,71	97	48	28,1	36,0	0,0	22	8,5	2,02	0,040	6,0	0,20	6,4	1,20	0,037	45	21
MZ11	6,60	24	12	27,8	20,5	0,0	7	3,5	2,20	0,060	2,5	0,10	2,80	0,10	0,011	7	6
MZ12	6,71	19	6	26,9	5,9	0,0	5	2,6	2,12	0,010	1,9	0,30	2,00	0,09	0,020	5	4
MZ13	6,92	59	30	28,5	12,7	0,0	19	8,0	1,01	0,040	6,0	0,10	4,6	1,20	0,214	17	16
MZ14	6,88	37	19	27,9	0,3	0,0	9	8,2	0,90	0,030	5,0	0,10	2,70	0,80	0,004	10	7
MZ15	7,17	132	66	27,1	0,1	0,0	61	11,0	0,96	0,070	8,0	0,90	16,0	2,70	0,003	51	50
MZ16	7,34	40	20	27,0	21,7	0,0	8	8,2	0,49	0,010	5,0	0,30	2,0	0,80	0,139	9	7
MZ17	6,77	51	26	27,3	25,3	0,0	15	7,0	3,90	0,110	5,7	0,80	3,6	0,90	0,166	13	12
MZ18	7,09	76	38	27,4	21,7	0,0	18	12,1	0,71	0,090	6,8	0,10	5,7	0,70	0,063	17	15

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