Challenges and solutions towards reaching SDG6 in Malawi

Rebekah Grace Kudakwashe Hinton

DOCTOR OF PHILOSOPHY

2024

“*Malawi: Shaped by Water*” by R Hinton

Declaration

I hereby declare that the work presented in this thesis has not been submitted for any other degree or professional qualification, and that it is the result of my own independent work.

R. Hinton

Rebekah Grace Kudakwashe Hinton

Date 24/04/2024

Abstract

Sustainable Development Goal (SDG) 6 outlines the aim to 'ensure access to water and sanitation for all' by 2030. For Malawi, this will require significant investment and development to ensure that the 82% of the population currently lacking safely managed drinking water, as well as the 54% currently lacking sanitation, gain access to these necessities. However, the additional requirement of developing the necessary capacity to meet the water and sanitation needs of a rapidly growing population makes meeting SDG6 a greater challenge. Malawi has a current population of 21 million but is expected to undergo a five-fold population increase in this century. A rapidly changing climate and subsequent increased frequency of extreme weather events make managing future risks to meeting SDG6 ever more complicated.

Groundwater is a central facet of Malawi's water security, providing over 80% of domestic water use as well as meeting significant agricultural, and industrial water needs. However, despite the centrality of groundwater to Malawi's water resources, the largely unseen nature of groundwater means that little is known about Malawi's most used water source. Limited resources and monitoring networks have further hampered efforts to monitor and manage groundwater resources.

To aid decision making in working towards achieving SDG6, this thesis applies data analysis and novel modelling techniques to better understand the current status of Malawi's water and sanitation as well as the future threats to reaching SDG6. Firstly, the thesis explores challenges to water security, considering both water quantity and quality to ensuring SDG6. Analysis of challenges to water quantity involves exploration of the interface between groundwater and surface water in Malawi as well as the application and development of a global hydrological model to represent a holistic view of water resources and provide the first system models of groundwater in Malawi. In considering water quality the thesis focuses on groundwater contamination from sanitation systems, identifying pit-latrines as the major source of high microbial and nutrient groundwater contamination nationally. A novel model of pit-latrine usage is developed to model contamination risks from pit-latrines under multiple scenarios of population growth and sanitation development. The 'paradox of SDG6' is considered whereby the reduction of open defecation, through the proliferation of pit-latrines, has the potential to result in dramatic levels of groundwater contamination.

In recognition of the impact of sanitation systems on water quality, the thesis then considers progress in sanitation and hygiene to SDG6. Trends in sanitation provision, and the implications for ensuring 'sanitation for all' are explored under future scenarios of population change. The sustainability of progress to sanitation provision is also explored, emphasising the need for not only sanitation provision but *sustainable* systems. Menstrual hygiene management is also discussed to consider the express focus on meeting 'the needs of women and girls' outlined within SDG6.

Finally, community-led solutions to the identified challenges of water security and sanitation provision in meeting SDG6 are explored using the case studies of borehole-garden permaculture and pit-latrine emptying. Not only do these provide examples of solutions integrating multiple challenges identified in both water security and sanitation, investigation of local level solutions also directly addresses SDG6 which emphasises the need to 'support and strengthen the participation of local communities in improving water and sanitation management' (SDG6.B).

By investigating both challenges and solutions to water and sanitation on both a local and national scale in Malawi, this thesis develops a holistic understanding of SDG6 in Malawi, emphasising the need to consider multiple aspects and scales of SDG6 together. The pressing challenges of population growth and climate change on water security and sanitation provision are underscored, highlighting the need for consideration of sustainably meeting future water and sanitation needs in decision-making. The methodologies and holistic framework developed in this thesis provide tools to monitor, manage and predict barriers to SDG6 not only for Malawi but also supporting progress to SDG6 on a global scale.

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of chats about toilets. Mostly, thanks to Charlie for every proofread and game test, for your unwavering support, and your continuous encouragement. I couldn’t have done it without you. May this thesis be dedicated to Charlie.

Preface

The core of this thesis was developed as series of papers which have been published, are in review, or are in preparation, for publication in peer reviewed journals. Each chapter contains individual papers with their own background, methodology, results, and conclusions. Each paper provides specific policy recommendations accordingly. Each chapter introduces the broad concepts and research questions, followed by the papers and discussion post-faces to the individual pieces. The paper references and author contributions are stated below:

Chapter 4

Paper 1

Disclaimer: This paper provides one aspect of the overarching conceptual framework for this thesis, but it is not key to the overall body of research the Author presents as a dissertation.

The final version this paper builds on various work from the wider research group, with critical publications currently in peer review. For timely submission of this thesis and to present the contribution to this paper, an outline draft is provided here with expectation of submission in May 2024.

The body of research submitted follows this work.

Kalin, R.M†., Hinton, R.G.K†, Riddel, L., Rivett, M., Mleta, P., Kanjaye, M., Kamutula, S., Wanangwa, G., Uka, Z., Ngongo, C. (*In Prep*). Groundwater Storage as a key temporal and spatial factor for surface water availability to Lake Malawi*. Water.*

†: Joint first authorship

Author contribution:

Conceptualization (R.M.K., R.G.K.H, L.R, R.M, P.M, M.K., S.K, G.W, Z.U, C.N), data curation (R.M.K), formal analysis (R.G.K.H, R.M.K, L.R), investigation (R.G.K.H, R.M.K, L.R), methodology (R.G.K.H, R.M.K, L.R), validation (R.G.K.H, R.M.K), visualization (R.G.K.H, R.M.K), project administration (R.M.K), supervision (R.M.K), writing original draft (R.G.K.H, R.M.K), review and editing (R.M.K., R.G.K.H, L.R, R.M, P.M, M.K., S.K, G.W, Z.U, C.N

Paper 2

Hinton, R.G.K., Smilovic, M., Fridman, D., Willaarts, B., Banda, L., Macleod, C. J. A., Troldborg, Kalin., R.M. (*Under review by co-authors*). Stakeholder informed approach improves national modelling of water resources for the Sub-Saharan African Basin. *Environmental Science and Technology.*

Author contribution:

Conceptualization (R.G.K.H, R.M.K, L.B.), data curation (R.G.K.H, M.S, D.F, W.B), formal analysis (R.G.K.H), investigation (R.G.K.H), methodology (R.G.K.H), validation (R.G.K.H), visualization (R.G.K.H), project administration (R.M.K), supervision (R.M.K, M.S, D.F, W.B, M.T., K.M), writing original draft (R.G.K.H), review and editing (R.G.K.H, R.M.K., M.S, D.F, W.B, C. J.A.M, M. T, M. K, L.B)

Chapter 5

Paper 3

Hinton R.G.K., Kalin, R.M., Kanjaye, M.B., Mleta, P., Macleod, C.J.A., Trolborg, M. (*In Review*). Spatial model of groundwater contamination risks from pit-latrines under multiple sanitation scenarios in a low-income country. *Water Resources.*

Author contribution:

Conceptualization (R.G.K.H, R.M.K, C.J.A.M, M.T, M.K), data curation (K.M, P.M, R.M.K), formal analysis (R.G.K.H), investigation (R.G.K.H), methodology (R.G.K.H), validation (R.G.K.H), visualization (R.G.K.H), project administration (R.M.K), supervision (R.M.K, C.J.A.M, M.T), writing original draft (R.G.K.H), review and editing (R.G.K.H, R.M.K., C. J.A.M, M. T, M. K, P.M)

Paper 4

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Author contribution:

Conceptualization (R.G.K.H, R.M.K, L.B., M.K.) data curation (R.G.K.H,L.B, R.M.K), formal analysis (R.G.K.H, L.B), investigation (R.G.K.H, L.B), methodology (R.G.K.H, L.B), validation (R.G.K.H, L.B), visualization (R.G.K.H, L.B), project administration (R.M.K), supervision (R.M.K, C.J.A.M, M.T), writing original draft (R.G.K.H), review and editing (R.G.K.H, L.B, R.M.K., C. J.A.M, M. T, M. K, V.P)

Chapter 6

Paper 5

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Author contribution:

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

Paper 6

Hinton, R.G.K., Tremblay-Lévesque, L.C., Macleod, C. J. A., Troldborg, M., Kanjaye, M., Kalin, R.M. (*In Review*). Progress and slippage of sanitation and hygiene targets in Malawi: is SDG6.2 achievable? *Journal of Water, Sanitation and Hygiene for Development.*

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Conceptualization (R.G.K.H, R.M.K, M.K., L.C.T.L) data curation (L.C.T.L R.M.K), formal analysis (R.G.K.H), investigation (R.G.K.H), methodology (R.G.K.H., L.C.T.L., C.J.A.M., M.T., R.M.K.), validation (L.C.T.L, R.G.K.H.), visualization (R.G.K.H), project administration (R.M.K), supervision (R.M.K, C.J.A.M, M.T), writing original draft (R.G.K.H), review and editing (R.G.K.H, L.C.T.L., R.M.K., C. J.A.M, M. T, M. K,)

Paper 7

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Author contribution:

Conceptualization (R.G.K.H, R.M.K,. L.C.T.L) data curation (L.C.T.L R.M.K), formal analysis (R.G.K.H), investigation (R.G.K.H), methodology (R.G.K.H., L.C.T.L., C.J.A.M., M.T., R.M.K.), validation (L.C.T.L, R.G.K.H.), visualization (R.G.K.H), project administration (R.M.K), supervision (R.M.K, C.J.A.M, M.T), writing original draft (R.G.K.H), review and editing (R.G.K.H, L.C.T.L., R.M.K., C. J.A.M, M. T, M. K,)

Chapter 7

Paper 8

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Conceptualization (R.G.K.H, C.J.A.M, M.T., R.M.K) data curation (R.M.K., G.W., M.K., E.M., P.M., K.H., S.K), formal analysis (R.G.K.H,), investigation (R.G.K.H, C.J.A.M, M.T., R.M.K., G.W., M.K., E.M., P.M., K.H., S.K), methodology (R.G.K.H., C.J.A.M., M.T., R.M.K.), validation (R.M.K., G.W., M.K., E.M., P.M., K.H., S.K), visualization (R.G.K.H), project administration (R.M.K), supervision (R.M.K, C.J.A.M, M.T), writing original draft (R.G.K.H), review and editing (R.G.K.H, C.J.A.M, M.T., R.M.K.)

Paper 9

Hinton, R. G. K., M., Kanjaye, Macleod, C. J. A., Troldborg, M. B. & Kalin, R. M. (*In review*). Evaluation of pit-latrine emptying practices as a solution to poor pit-latrine construction quality: the case of Malawi. *Hygiene and Environmental Health Advances*

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In addition to the papers published, the work presented here has been presented at international conferences detailed below:

Hinton, R.G.K., Smilovic, M., Fridman, D., Willaarts, B., Banda, L., Macleod, C. J. A., Troldborg, Kalin., R.M. 2024. A stakeholder driven, holistic water resources model for Malawi: applying the CWatM hydrological model. EGU General Assembly Conference. EGU24-5783. 15-19 April 2024.

Hinton, R.G.K., Loades, K., 2024. WellPlaced: Cooperatively navigating challenges to land and water management to reach SDG6. EGU General Assembly Conference. EGU24-17108. 15-19 April 2024.

Hinton, R.G.K, Banda, L., Macleod, C., Troldborg, Kalin, R., 2023. Trends in pit-latrine usage in Malawi and their unintended impacts on groundwater quality. EGU General Assembly Conference. EGU-6720. 23–28 Apr 2023.

Hinton, R. G. K., Macleod, C. J. A., Troldborg, M., Wanangwa, G., Kanjaye, M., Mbalame, E., Mleta, P., Harawa, K., Kumwenda, S. & Kalin, R. M., 2022. Factors influencing the awareness and adoption of borehole-garden permaculture in Malawi: lessons for the promotion of sustainable practices. 5th Groundwater SADC Conference, Windhoek. Virtual Oral Presentation. 16-18 Nov 2022.

Hinton, R. G. K., Macleod, C. J. A., Troldborg, M., Wanangwa, G., Kanjaye, M., Mbalame, E., Mleta, P., Harawa, K., Kumwenda, S. & Kalin, R. M., 2022 Factors influencing the awareness and adoption of borehole-garden permaculture in Malawi: lessons for the promotion of sustainable practices. EGU General Assembly Conference. EGU22-13160. 23-27 May 2022.

Invited presentations:

In addition, the work was presented at invited talks, detailed below:

Scottish Environment Food and Agriculture Research Institutes (SEFARI) Showcase of Postgraduate Research (2022) Buried treasure: Protecting Malawi's groundwater resources. Royal Society, Edinburgh. 29-30 October 2022.

Scottish Environment Food and Agriculture Research Institutes (SEFARI) Showcase of Postgraduate Research. (2023). Securing Malawi's Water Future: Challenges in reaching SDG6. Royal Society, Edinburgh 26-27 Oct 2023.

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UKRI, NERC. Awarded to undertake Young Scientists Summer Project (YSSP) placement at the International Institute of Applied Systems Analysis (IIASA). (£5,000), project 'Securing Malawi's Water Future'. 2023.

Table of Contents

List of abbreviations and acronyms

BGP: Borehole-garden Permaculture

BIC: Baysien Information Criterion

CJF: Climate Justice Fund

CWatM: Community Water Model

DHS: Demographic Health Survey

GIS: Geographic Information System

GLM: Generalised Linear Model

GLMM: Generalised Linear Mixed Model

GoM: Government of Malawi

GRACE: Gravity Recovery and Climate Experiment

JMP: Joint Monitoring Project

KGE: Kling Gupta Efficiency

LMRSB: Lake Malawi Shire River Basin

MDG: Millenium Development Goal

MIS: Malaria Indicator Survey

MK: Malawian Kwacha

NGO: Non Government Organisation

NSE: Nash-Suttclife Efficiency

OD: Open Defecation

ODF: Open Defecation Free

RF: Random Forest

RIFR: Reneweable Internal Freshwater Resources

RMSE: Root Mean Squared Error

RQ: Research Question

SADC: Southern African Development Community

SC: Spearman Correlation

SDG: Sustainable Development Goal

SO: Specific Objective

SSP: Shared Socioeconomic Pathways

SWAT: Soil and Water Assessment Tool

TWS: Total Water Storage

UFSF: Urban Fraction Smoothing Factor’

UN: United Nations

UNICEF: United Nations Children's Fund

VIF: Variance Inflation Factor

WaSH: Water, Sanitation, and Hygiene

WHO: World Health Organization

WP: Water-point

WPC: Water-point Committee

WRA: Water Resource Area

WRU: Water Resource Unit

List of figures*

* Tables and figures found within papers forming the research chapters 4-7 are not listed here and can be found in the specific papers.

Chapter 1: Introduction

Madzi ndi Moyo"

Chichewa expression

"Water is life".

Chapter 1: Introduction

1.1 Overview

In recognition of the central role of water and sanitation for environmental and public health, Sustainable Development Goal 6 (SDG6) aims to ensure access to clean water and sanitation for all by 2030. It encompasses targets related to safe drinking water access, adequate sanitation, water quality improvement, water scarcity mitigation, cooperation in water governance, ecosystem protection, and community participation. Due to of the interconnectivity of water security, environmental sustainability, public health, and socio-economic development within SDG6, this thesis proffers a holistic approach to SDG6. The thesis is specifically focused on applying a holistic perspective and innovative methodology to inform water and sanitation management in Malawi.

Malawi faces significant challenges in meeting SDG6 targets with rapid population growth, infrastructure failure, and climate change impacts being just some of the challenges in achieving this goal. Despite efforts to improve access to sanitation and water, a considerable portion of the population still lacks adequate facilities, leading to issues such as open defecation and waterborne diseases. Climate-related events exacerbate these challenges, with flooding and in particular posing significant risks to public health and infrastructure. Addressing these issues, both now and for the future, requires informed policy and investment in water resource management and sanitation infrastructure, coupled with community engagement.

This thesis sits within a wealth of research and engagement between researchers and policy makers within Malawi and Scotland. Specifically, this research comes under a Scottish Government funded programme: the 'Climate Justice Fund: Water Futures Programme' granted to the University of Strathclyde in 2011. A central part of this programme was the implementation of two nationwide surveys of sanitation and water infrastructure, providing the most detailed water and sanitation specific infrastructure information for Malawi. The surveys, conducted from 2012-2020, involved hundreds of Government of Malawi trained enumerators and thousands of surveys conducted at the community and household level. A lack of understanding of some of the challenges facing this infrastructure, and consequently Malawi's progress of SDG6, was identified as a key area of focus by stakeholders within the Government of Malawi and forms the foundation for this research. Investigation of some of these challenges highlighted the importance of ensuring a holistic outlook to multiple areas of SDG6 and inspired the aim of developing a holistic perspective presented within this thesis, enabling identification of both conflicts and synergies to SDG6.

1.2 Research Aim and Objectives

1.2.1 Research Aim

The aim of this thesis was to contribute to the holistic understanding of the challenges and solutions involved in achieving Sustainable Development Goal 6 (SDG6), with a focus on the context of Malawi.

The thesis will ensure a holistic focus by looking at multiple levels of scale, focus, and subjects, Figure 1.1.

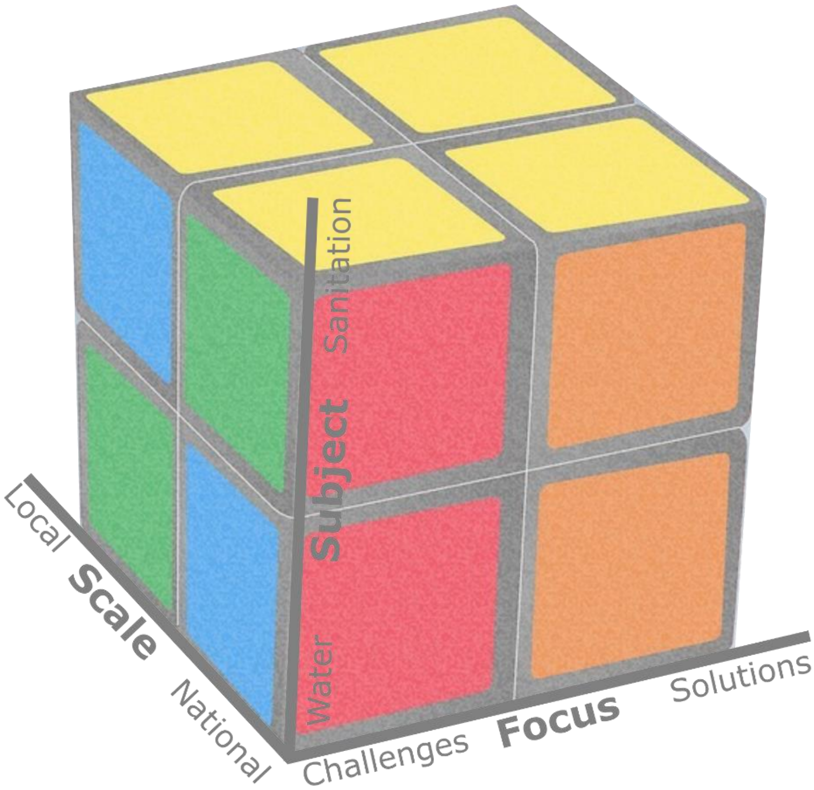


Figure 1.1: The multiple areas explored within this thesis to develop a holistic perspective of sanitation and water in Malawi

The motivation for this aim stems from the fragmented nature of water and sanitation policies despite their inherent interconnectivity. The thesis is presented to inform policy maker and donor decisions in Malawi's water and sanitation initiatives, maintaining stakeholder interests at the centre. Stakeholder concerns regarding various aspects of water management, sanitation, and hygiene in meeting SDG6 were used to develop specific areas of focus and underscore the importance of this research.

To achieve this aim, the thesis formulates 4 research questions, each accompanied by specific objectives, discussed below.

1.2.2 Research questions and objectives

The research questions address both challenges and solutions to SDG6. Research questions (RQs) 1,2 and 3 focus on *challenges* within the areas of water quantity, water quality, and sanitation whilst RQ4 explores *solutions* within water security and sanitation. Each RQ is composed of several Specific Objectives (SOs).

Figure 1.2 shows the structure of the research questions and specific objectives within this thesis and how they connect to specific publications.

1.2.3 Challenges to SDG6

1.2.3.1 ***Challenges to water security in Malawi***

RQ 1: What are challenges to water scarcity in Malawi?

SO1: Explore the influence of groundwater on surface water security by evaluating the interaction of groundwater to Lake Malawi water storage.

SO2: Develop a model of groundwater storage in the transboundary Lake Malawi Shire River Basin.

SO3: Explore changes in groundwater storage within the Lake Malawi Shire River Basin.

RQ 2: What are challenges to water quality in Malawi?

SO4: Evaluate current pit-latrine groundwater contamination risks from pit-latrine proximity using sanitation and water infrastructure data.

SO5: Develop a model to predict future groundwater contamination risk from pit-latrines under multiple scenarios of population growth and sanitation development.

SO6: Use water quality data to explore drivers of contamination of groundwater drinking water supplies.

1.2.3.2 Challenges to sanitation and hygiene provision in Malawi?

RQ3: What are challenges to sanitation and hygiene provision in Malawi?

SO7: Evaluate current provision of sanitation in Malawi, specifically addressing significant variation in estimates of improved sanitation access.

SO8: Predict future progress of sanitation provision and ending open defecation under multiple population growth scenarios.

SO9: Explore sanitation within communities declared open defecation free to investigate the sustainability of open defecation elimination.

SO10: Evaluate current hygiene provision exploring access to handwashing as well as menstrual hygiene management. Identify barriers to hygiene provision.

1.2.4 Solutions for SDG6

1.2.4.1 Local solutions to challenges to meeting SDG6

RQ4: What are local solutions to Malawi's water and sanitation challenges?

SO11: Explore the example of borehole-garden permaculture as a local-level sustainable water use practice. Specifically, evaluate what influences both awareness of adoptions?

SO12: Explore the example of pit-latrine emptying as a local example of sanitation management. Investigate whether pit-latrine emptying be used to improve pit-latrine construction quality?

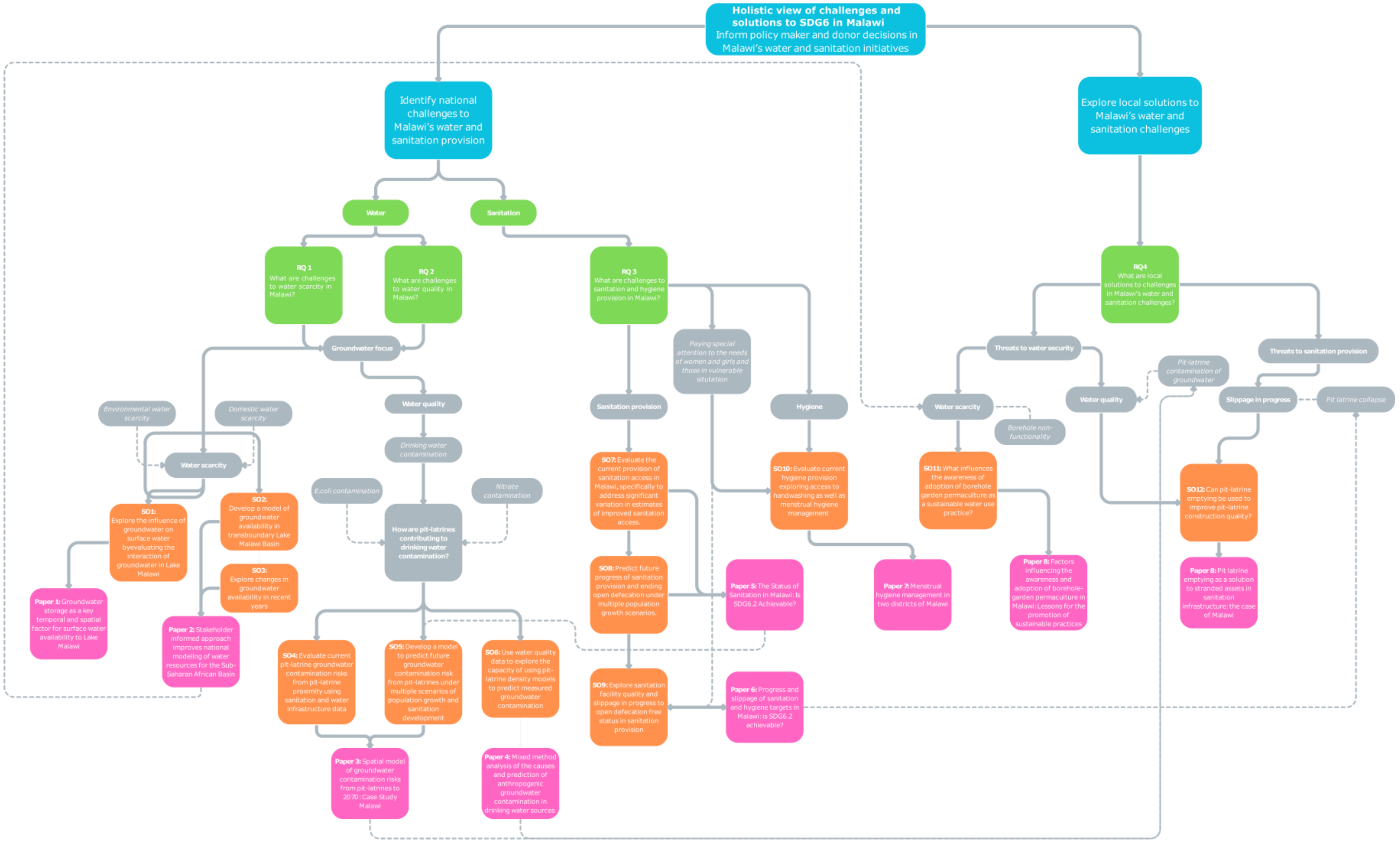


Figure 1.2: Overall thesis structure. The aim of the thesis, and aims of the component parts are provided in blue. Research questions are given in green boxes with specific objectives in orange boxes. The specific objectives feed into papers presented here (pink boxes).

1.3 Thesis structure

This thesis is composed of 9 chapters and an appendix. The chapters are an introduction, background, methodology, 4 research chapters, a discussion, and conclusions and recommendations. The 4 research chapters each contain peer review papers (published, submitted or in draft). As individual publications, references for each publication are provided at the end of each paper in the style appropriate to the journal.

Chapter 1 (introduction) provides an overview of the research topic and aim of the thesis. The chapter details how the 4 research questions identified will be addressed through 12 specific objectives and outlines the structure of the thesis.

Chapter 2 (background) provides the context of the thesis, giving insight into sustainable development goal 6 (in the context of the previous millennium development goals and within the setting of the sustainable development goals). The chapter then provides background to the study context of Malawi, specifically focusing on water and sanitation challenges in Malawi. Finally, the chapter outlines some of the ways mathematical modelling has been used to develop understanding of challenges in water, sanitation, and hygiene.

Chapter 3 (methodology) provides an overview of some of the commonly used methods within this thesis, giving context to their use. It should be noted that the papers which make up each individual research chapters (4-7) include their own methods sections, explaining the specific methods used in each case, chapter 3, therefore, provides a broad overview.

Chapter 4 is the first research chapter and focuses on challenges to water quantity within Malawi, answering RQ1 through SO1, SO2, and SO3. The chapter considers water scarcity with a focus on groundwater. The connection between surface water and groundwater is evaluated using the case of Lake Malawi's water storage. The chapter then addresses the challenge of limited data surrounding Malawi's groundwater supplies through the development of a hydrological model of the Lake Malawi Shire River Basin, which is used to evaluate the status of, and change in, Malawi's groundwater storage. The chapter emphasises that growing insecurity in Malawi's groundwater threatens Malawi's water resources, both groundwater and surface water.

Chapter 5 addresses the challenge to water quality within Malawi, answering RQ2 through SO4, SO5, and SO6. The chapter focuses on faecal water contamination due to the significant burden of waterborne disease in Malawi. The risk of faecal water contamination from pit-latrine infrastructure is highlighted as a particular area of focus, developing a novel method to evaluate the risk of contamination to water-points from pit-latrines. This is used to explore future projections of risk to water-points from pit-latrines under multiple scenarios of population growth and sanitation policies. Water quality data is evaluated to identify the major drivers of contamination (both microbial and nutrient) in Malawi, identifying sanitation related infrastructure as significant causes of contamination.

Chapter 6 leads on from the identification of sanitation infrastructure as a major consideration in water quality to explore Malawi's sanitation provision. Specifically, this chapter evaluates challenges in sanitation and hygiene provision, answering RQ3 through addressing SO7, SO8, SO9, and SO10. The chapter identifies multiple challenges in both current and future sanitation and hygiene provision finding major challenges in current sanitation infrastructure as well as revealing the current rate of sanitation provision to be inadequate to meet the needs of a growing population. In addition, the sustainability of steps to eradicate open defecation is evaluated revealing a reversal of progress and suggesting that a short-term focus in eradicating open defecation may limit long-term sanitary provision. Recognising the importance of improvement to sanitation in tandem with hygiene provision, the extent of hygiene provision is explored considering challenges to both handwashing and menstrual hygiene management.

Chapter 7 focuses on solutions to some of the challenges identified in this thesis, answering RQ4 through achieving SO11 and SO12. The chapter draws on two examples of local level solutions, evaluating the case of borehole-garden permaculture as a solution to challenges of water quantity identified in chapter 4. Pit-latrine emptying is also investigated as a solution to challenges of water quality and sanitation provision highlighted in chapters 5 and 6 respectively. Barriers to the adoption of both local-level solutions are identified.

Chapter 8 discusses multiple aspects of the research presented in chapters 4-7. The chapter addresses why a holistic view of SDG6 is needed to address multiple barriers, identify inter and intra-goal conflicts and synergies within achieving SDG6 and sustainable development.

Chapter 9 concludes the thesis, providing an overview of the key findings and contributions of the thesis. The chapter provides specific policy recommendations from the paper, meeting the goal of informing policy maker and donor decisions. The chapter concludes with a discussion of future research recommendations.

The Appendix provides an overview of some of the ways in which the findings of this thesis have been communicated. Firstly, an overview is given of the boardgame 'WellPlaced' which has been developed to explore some of the challenges in reaching SDG6 discussed within this thesis. Secondly, an article, considering some of the challenges in water and sanitation in Malawi written for 'Appropriate Technology' is provided which focuses on communicating some of the challenges and solutions explored in the thesis in a format that is widely accessed by stakeholders.

Chapter 2: Background

"The beginning of knowledge is the discovery of something we do not understand".

Frank Herbert, 1981

Chapter 2: Background

2.1 Introduction

Access to clean water and sanitation are fundamental human rights. However, ensuring progress in supplying clean water and sanitation is a challenge, particularly in regions facing rapid population growth and environmental change. This thesis delves into the challenges and solutions for reaching Sustainable Development Goal 6 (SDG6), clean water and sanitation for all, in Malawi. The thesis applies mathematical modelling to explore the current situation, investigate trends, and suggest the future of challenges and solutions within SDG6. The work touches on all aspects of SDG6, exploring dynaMICS in water, sanitation, and hygiene.

This chapter provides background to the area of focus and the methods used in this thesis. An overview of SDG6 and where it fits within the wider context of the sustainable development goals is given. The specific nature of water and sanitation management in Malawi is then explored, considering some of the challenges for Malawi's path to SDG6. The chapter then provides an overview of mathematical modelling, giving insight into its purpose and how it can be used to develop understanding of SDG6. Finally, reflecting on all these areas, the chapter identifies specific knowledge gaps of the challenges and solutions in reaching SDG6 in Malawi.

2.2 Sustainable Development Goal 6

Following on from the Millennial Development Goals (MDGs), established in 2000 (to be met in 2015) (United Nations, 2015), the Sustainable Development Goals (SDGs) set out global aims to be reached over the subsequent 15-year period to 2030 (UN General Assembly, 2015). As with the MDGs, the SDGs worked to outline a global development agenda, guiding collaborative efforts to pave the path for a more equitable and sustainable future with a focus on 'leaving no one behind'. Whilst the MDGs outlined 8 goals for global efforts, the SDGs extended these to 17 goals, placing a particular emphasis on environmental sustainability in all aspects of socioeconomic development (United Nations, 2015). The 8 MDGs and 17 SDGs are summarised in Figure 2.1.

Figure 2.1: The 8 Millenium development goals (MDGs) and subsequent 17 sustainable development goals (SDG6s). Image for the SDGs from United Nations SDGs online (United Nations, 2024).

The MDGs recognised the importance of sanitation and water, specifically outlining the goal to "halve the proportion of people without sustainable access to safe drinking water and basic sanitation by 2015", within MDG 7C (United Nations, 2015). By 2012, the component of this goal relating to safe drinking water had been met, with 34% of the global population reported to use an unimproved water source in 1990, falling to under 10% by 2015 (United Nations, 2015).

However, progress on sanitation access lagged, failing to halve the number of people practising open defecation from 1990-2015 (United Nations, 2015).

It was only within the SDGs that improvement to water and sanitation were laid out as a specific area of focus within their own goal; SDG6 'clean water and sanitation for all'. SDG 6 reflects a broader and more ambitious commitment to ensuring universal access to safe and affordable drinking water, adequate sanitation, and proper hygiene practices by 2030 (UN General Assembly, 2015). It builds upon the progress made under the MDGs while incorporating a more holistic approach that emphasizes sustainability, integrated water resource management, and the protection of water-related ecosystems. SDG6 is broken into 8 targets each with specific indicators to monitor progress (WHO & UNICEF, 2023), Figure 2.2.

Figure 2.2: The 8 targets within SDG6. Each target has specific indicators intented to assist in monitoring of progress.

The 8 goals within SDG6, and the connections between, them are summarised in Figure 2.3. The first target (6.1) specifies the goal to achieve universal and equitable access to safe and affordable drinking water for all by 2030; SDG6.1 recognises the multiple challenges of water security provision at the intersectionality of water quantity quality and access notably recognising the challenge of economic water insecurity (Seckler and International Water Management Institute, 1998). Target 6.2 relates to sanitation provision specifying the goal to achieve adequate and equitable sanitation and hygiene for all and to end open defecation. The target places particular focus on the needs of women and girls and those in vulnerable situations emphasising current gender inequality in sanitation insecurity (Grant et al., 2017). Target 6.3 focuses on water quality, recognising the significance of preventing contamination for both drinking water provision and ecological protection. The target focuses on reduction of pollution including from hazardous chemicals, notably from industrial sources as well as wastewater. Target 6.4 emphasises the challenge of water scarcity and the need for an increase in water use efficiency, specifying the goal to increase water use efficiency across all sectors and ensure sustainable withdrawals. The target responds to the large number of people suffering from water scarcity globally; it is estimated that over 4 billion people experience severe water scarcity for at least one month of the year (Mekonnen and Hoekstra, 2016). Targets 6.5 and 6.a focus on water cooperation; 6.5 focuses on implementing integrated water management and focuses on transboundary cooperation whilst 6.a focuses on supporting developing countries in water related activities and programmes. Target 6.6 places a heavy emphasis on the ecological component of water security and water management decisions in both protecting and restoring water related ecosystems. Finally, target 6.b focuses on the significance of local communities in progress to SDG6 specifying the goal to support and strengthen participation from local communities in improving water and sanitation management. Within these 8 goals SDG 6 addresses multiple challenges in water security and sanitation provision. Whilst the targets within SDG6 are considered as individual goals with specific indicators to enable progress to be measured, it should be emphasised that, as with the case of all the sustainable development goals, the specific goals within SDG6 are highly inter interconnected, with potential for both synergy and conflict, as summarised in Figure 2.3.

Figure 2.3: The highly interconnected nature of SDG6. The targets within SDG6 are represented by coloured boxes, relating to figure 2.2, and connected to the central SDG6 goal by blue arrows. Indicators within SDG6 targets are shown in lilac with grey solid arrows. Areas of focus (but not targets) are in grey. Grey dashed arrows represent connections between SDG6 targets.

2.3 Progress and challenges in SDG6 in Malawi

This thesis focuses on Malawi, a country situated in South-Eastern Africa, Figure 2.4. Malawi currently has a population of 21 million, however, this is rapidly growing, with an annual growth rate of 2.6% (NPC, 2020), it is anticipated that Malawi's population will increase five-fold this century (United Nations, 2020). Urbanisation is also presenting another radical demographic change; the percentage of the population living in urban areas is anticipated to undergo a four-fold increase over the next 40 years, with the proportion of the population living in rural areas anticipated to drop from 84% currently to 40% by 2060 (NPC, 2020). Providing appropriate housing, sanitation and water provision for a growing and urbanising population will be a challenge; inadequate housing provision can already be seen in that 60% of the current urban population currently reside in slum areas often with inadequate living conditions (NPC, 2020).

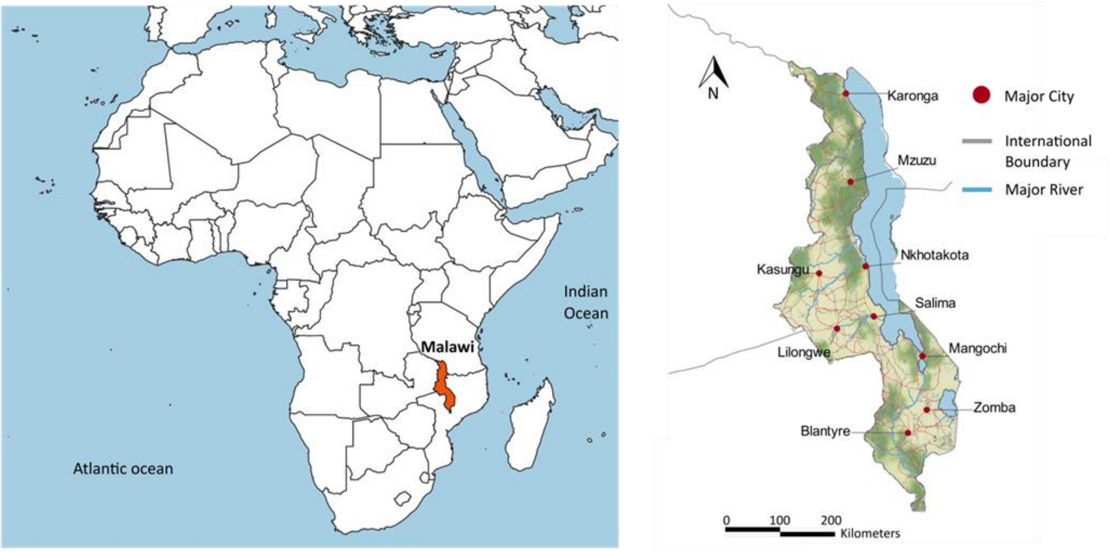


Figure2.4: This thesis focuses on Malawi, (shown in orange within Africa). The major cities are shown here.

2.3.1 Water resources

The economic landscape of Malawi plays a pivotal role in assessing its water and sanitation resources. The nation is predominantly agrarian, with over 80% of its population engaged in smallholder agriculture (NPC, 2020). Agriculture, largely as cropland (Li et al., 2021), occupies 64.2% of Malawi's land area (as of 2021) (World Bank, 2024). Although smallholder farmers primarily rely on rainfed agriculture, there has been a significant upsurge in smallholder irrigation, with an estimated 59,655 hectares of land under irrigation in 2019, up from 41,053 hectares in 2016 (Chafuwa, 2017; Government of Malawi, 2019). The Government of Malawi has specified an aim to increase smallholder irrigation at a 2% annual rate although actual growth has only been at a 1% rate since 2004 (Wiyo and Mtethiwa, 2018). Such expansion of smallholder irrigation will place an increasing demand on Malawi's water resources. Alongside intensification of small holder agriculture, planned commercial agricultural intensification projects (ERM, 2013; SAGCOT, 2024) are poised to exacerbate water resource pressure. Malawi's heavy reliance on agriculture renders its economy and populace particularly susceptible to climatic disturbances. Moreover, as one of the world's poorest countries, with over 70% of its population living below the international poverty line of $2.15 per day (Worldbank, 2024), economic constraints limit Malawi's ability to invest in climate-resilient infrastructure.

In addition to the implications of climate change on agriculture and economic development, extreme weather events have significant consequences for clean drinking water access in achieving SDG6.1. Currently, 82% of the population lack access to safely managed drinking water (UN, 2023) placing Malawi below the Sub-Saharan African average of 31% of the population having safely managed drinking water access (UN, 2023). Groundwater is a central component of Malawi's drinking water supplies, used as the main source of drinking water by over 80% of the population (Graham & Polizzotto, 2013); boreholes and tube wells comprise 64% of the improved sources of drinking water in the country (NSO, 2021). Contamination is a major issue for the provision of clean drinking water; 60% of the population relies on drinking water sources containing measurable *E. coli,* failing to meet WHO guidelines for safe drinking water (NSO, 2021). Increases in *E.coli* contamination of boreholes have been reported following extreme weather events, notably flooding in the aftermath of cyclone Idai (Rivett et al., 2019), posing a concern for future water quality under an increased frequency and intensity of extreme weather (Zeufack et al., 2021). Malawi has already witnessed an increased frequency of extreme weather events, notably flooding, a story echoed across much of Sub-Saharan Africa where there has been a 10-fold increase in the number of floods relative to 1970-1979 (Zeufack et al., 2021). Understanding the risks of faecal water contamination will be a central component on building climate resilience and ensuring progress to SGD6.

Malawi's capacity to meet domestic water resource requirements are also threatened by water scarcity in which the amount of fresh water available cannot meet water demand. This is commonly seen in the case of seasonal water scarcity where water is inaccessible at given points of the year. Within Malawi, approximately 10% of boreholes experience dry season water shortages (Kalin et al., 2019). A high prevalence of borehole non-functionality further hampers domestic water security, threatening progress to SDG6; 40% of boreholes are partially or completely non-functional, this represents a significant concern to water availability (Kalin et al., 2019).

Groundwater is not only a vital resource for Malawi's domestic water needs, it is also used widely in agriculture and industry. In rural areas, groundwater accounts for 82% of domestic, agricultural, and industrial water use (Chavula, 2012, as cited in Fraser et al., 2020). Moreover, even in contexts where surface water is utilised, surface water resources are dependent on groundwater with the majority of river flow coming from groundwater, particularly in the dry season where baseflow accounts for 97% of river flow (Kelly et al., 2019).

2.3.2 Sanitation and hygiene

Sanitation and hygiene are central components of SDG6, outlined specifically within SDG6.2. They are critical for ensuring environmental and public health and are integral for economic growth and development. In 2012 it was estimated that Malawi loses an average of $57 million per year from inadequate sanitation and hygiene, representing over 1% of national GDP (UNICEF Malawi, 2024).

Estimates regarding access to sanitation in Malawi vary widely. Malawi witnessed a significant decline from 27.7% of the population practicing open defecation in 1992 to current estimates of 6.7% (Government of Malawi, 2021; NSO and Macro International, 1994). Currently, 21% of the population are estimated to have access to safely managed sanitation, just below the sub-Saharan Africa regional estimate of 24% (UN, 2023). However, there are great variation of estimates of access to sanitation; the 2015/16 DHS and the 2018 Census reported that 55.1% and 63.8% of the population used improved sanitary facilities, respectively (NSO, 2018), contrasting Government of Malawi and UNICEF estimates of 35.2% (NPC, 2020) and 24.2% (UNICEF 2020) respectively in 2020. Variation in estimates of sanitation access, often resulting from changes in definition or monitoring metrics, hamper efforts to evaluate trends and progress.

As in the case of water resources, Malawi's progress to securing sanitation provision is hampered by the demands of a rapidly growing population (Hinton et al., 2023) alongside challenges of climatic events, notably flooding (Rivett et al., 2022). The rapidly growing population may limit Malawi's capacity to keep up with sanitation requirements, potentially resulting in an increase in the percentage of the population without access to sanitation even if there is an increase in the absolute number of people with access to basic sanitation. An increase in the open defecation, has already been observed with open defecation risisng from 6.2% in 2017 to 6.7% in 2022 despite ongoing investment into expanding sanitation infrastructure (Government of Malawi, 2021). Increases in the number of people without access to sanitation and slippage in progress to SDG6 not only come from the challenges of meeting population requirements but are also exacerbated by climatic events. Pit-latrine collapse, often due to extreme rainfall, poses a major challenge to long-term sanitation provision, potentially resulting in people returning to open defecation and reversal of progress to SDG6 (Cavill et al., 2015; Kouassi et al., 2023; Mosler et al., 2018). Ensuring progress to SDG6.2 requires consideration of these dual challenges.

Hygiene is another critical component of achieving SDG6.2. Hygiene encompasses a range of behaviours including handwashing, bathing, and menstrual hygiene (WHO and UNICEF, 2022). Water, sanitation, and hygiene are intrinsically connected, challenges arising in the provision of any of these areas threaten to undermine the others. Handwashing and menstrual hygiene management (MHM) are two central hygiene practices and areas of focus for achieving access to adequate hygiene within Malawi. Yet despite its centrality within public health and achieving SDG6, hygiene access is particularly low in Malawi with only 10% of households having access to basic hygiene (this is notably lower than the 67% of households with access to basic drinking water and 42% of households with basic sanitation) (UNICEF Malawi, 2018). Lack of hygiene is notably higher in rural settings with less than half as many households having basic hygiene access within rural settings than urban settings (8% and 18% access respectively) (UNICEF Malawi, 2018). Handwashing a is particular consideration in hygiene provision, the 2019-2020 National UNICEF MICS survey assessed handwashing access, finding that 25% of households had no handwashing facility and of those households with handwashing facilities, only 28% had facilities with soap and water (NSO, 2021). MHM is another critical hygiene consideration and one that is poorly understood within Malawi. Whilst it is estimated that 97.3% of women use appropriate menstrual absorbents (NSO, 2021), challenges still exist in MHM including stigmitisation (Vaughn et al., 2013; Kambala et al., 2020). Understanding barriers to hygiene (including handwashing and MHM) necessitates consideration not only of access to hygiene resources but also practice, considering culture and context.

2.4 Modelling SDG6

This thesis adopts a range of mathematical techniques to inform understanding of Malawi's current and future progress to SDG6. In this section, an overview of what mathematical modelling is and how it is used is provided alongside how mathematical modelling can be specifically applied to developing understanding of challenges and solutions in SDG6.

2.4.1 Mathematical modelling and its purpose

One of the most valuable attributes of mathematical modelling is its capacity to conceptualise complex scenarios and problems. These are often applied to the context of 'real-world' scenarios, providing simplified or abstracted summarises of the world around us; as described by Haines and Crouch, 2007, 'A mathematical model is a cyclical process in which real-life problems are abstracted, mathematised, solved and evaluated' (Haines and Crouch, 2007). Similarly, Verschaffel et al., define a mathematical model as 'the application of mathematics to solve problem situations in the real world' (Verschaffel et al., 2002). From a data science perspective, the 'real-world' is considered more as a dataset to be analysed or conceptualised, 'the goal of a model is to provide a simple low-dimensional summary of a dataset' (Wickham and Grolemund, 2017).

However, mathematical models can go beyond only representing the 'real world', they can also provide insight into conceptual systems or *ways of thinking*. Lesh & Doerr stress this distinction, noting that 'A model consists of both conceptual systems in learner's minds and the external notation systems of these systems'(Lesh & Doerr, 2003 as cited in Erbaş et al., 2014). This emphasises the capacity of models not only to represent 'real world' situations but conceptualisations and perceptions. In both cases, the mathematical model is taking a complex set of information and providing a framework to represent the reference system.

Others emphasise the role of the *modelling process itself* over the model produced. Lesh and Doerr highlight the value of the *process* of modelling as a vital knowledge step in understanding real world systems 'descriptions, explanations and constructions are not simply processes used on the way to produce "the answer"'(Lesh and Doerr, 2003). As such, they coin the term '*model eliciting'* processes, emphasising how both the modelling process and model itself should be considered as the goal (Lesh and Doerr, 2003). Sriraman echoes the call for recognising the value of both the model and modelling process, although still retains that these should be seen as distinct values, suggesting that 'modelling is used to refer to the processes employed *to model* a problematic situation. Model refers to the product, typically a physical symbolic or abstract representation' (Bharath Sriraman, 2006). This highlights the value that can be found in both the model created and the modelling process itself. This necessitates a continuous feedback process and cyclical process, as shown in Figure 2.5 (Haines et al., 2000).

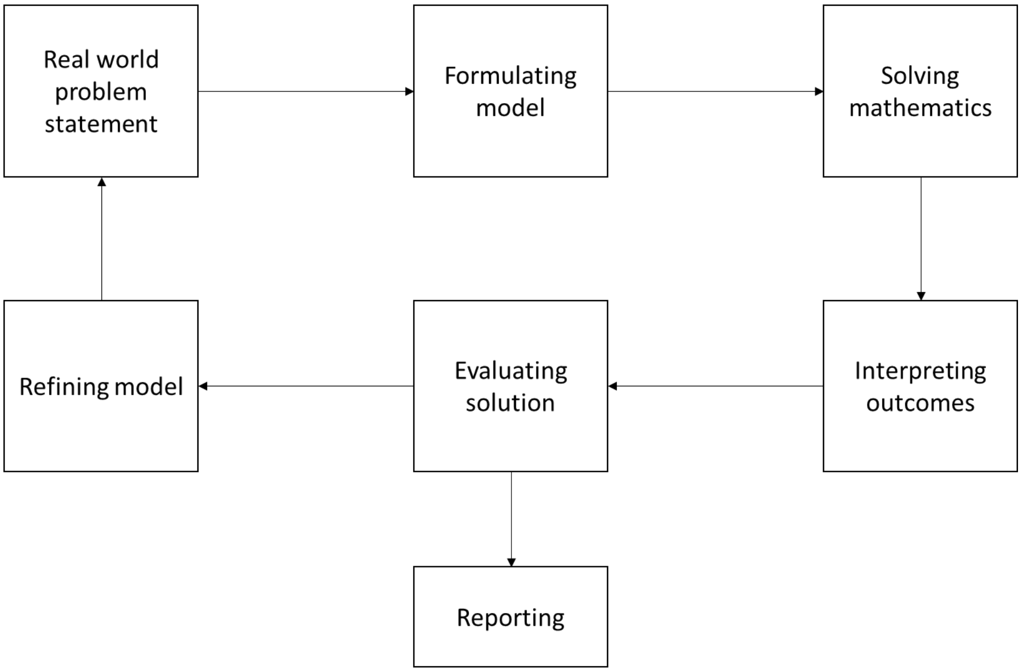


Figure 2.5: Cyclical model structure of mathematical modelling proposed by Haines et al., (2000).

Whether focusing on the value of the mathematical models itself or the modelling process, mathematical models are *simplified representations* of complex systems or datasets. As simplified representations, their worth perhaps lies most in *how* they are used, recognising their shortcomings, and taking value from both the modelling process, as well as the model itself. The value of mathematical modelling perhaps is best encapsulated George Box's much quoted epigram 'All models are wrong, but some are useful' (Box, 1979). The art of modelling may therefore be in separating out the 'wrong' and the 'useful'.

2.4.2 Modelling progress towards SDG6

Recognising their value in explaining real world phenomena, finding solutions, and predicting future scenarios it is perhaps unsurprising that mathematical modelling has been widely applied to inform progress towards sustainable development (Singh, 2014). This thesis focuses specifically on the application of mathematical modelling to study aspects of SDG6. Modelling has been used previously to explore aspects of SDG6, water and sanitation, in numerous contexts around the world (Germann et al., 2023; Miao et al., 2023; Roy and Pramanick, 2019). Here, a distinction is drawn between models used to develop *current understanding* and those which aid in *predicting the future* of progress towards SDG6.

2.4.2.1 Modelling current understanding

Progress to SDG6 is regularly monitored to inform understanding of progress. The UNICEF and WHO Joint Monitoring Programme (JMP) are responsible for global monitoring efforts of targets relating to water, sanitation, and hygiene; the organisations together act as custodian agents for SDG6.1, and SDG6.2 (JMP, 2024). Data analysis and visualisation techniques are often applied to data collected in monitoring progress to SDG6, helping to reveal and patterns track change. The use of mathematical modelling can help to overcome limitations in the scope and explanatory power of monitoring data, these are further explored here with specific examples of their applications to aspects of SDG6.

2.4.2.1.1 Mathematical modelling to fill data gaps

Monitoring progress towards SDG6 can be costly, time consuming, and challenging, particularly in locations with limited infrastructure (Barzegar et al., 2023). Modelling approaches can be used to enhance monitoring, providing inference tools to predict patterns in SDG6 targets by measuring and monitoring alternative metrics or to predict indicators in locations where measurements cannot be made.

Example: water quality inference through artificial learning approaches

Water quality monitoring is an example of one area where mathematical modelling and inference tools have been used to enhance understanding of the current progress towards SDG6. Models based on machine learning and artificial intelligence processes have value in this field to predict overall water quality from water quality indicators (Barzegar et al., 2023; Jena et al., 2023; Mei et al., 2022). This is particularly beneficial in predicting indicators that are costly to measure *in-situ* , such as *E.coli* level. Measuring *E.coli* levels is time-consuming and often involves impractical field data collection processes (Mei et al., 2022). Where limited data is available, indicators which relate to socioeconomic variables can be used to suggest locations likely to have poor drinking water quality. This has been seen in the application of nighttime lights (Mukherjee et al., 2019) and other development variables (Bruederle and Hodler, 2018) to aid in the identification of areas which are likely to have poor water quality. Areas identified can then be used to guide field data water quality surveying efforts where limited resources are available to conduct such assessments.

2.4.2.1.2 Mathematical modelling to explain data

Another limitation of monitoring SDG6 progress, is understanding barriers to progress and developments of appropriate water and sanitation infrastructure. Mathematical modelling techniques can aid interpretation of the barriers reaching SDG6.

Example: sanitation access and socioeconomic drivers

Celeste *et al.,* 2023 applied mathematical modelling to understand the socioeconomic drivers of access to sanitation in the Philippines. Application of a classification and regression tree was used to investigate the relationships between sanitation access, water sources and wealth, identifying poverty levels as a major driver of poor sanitation (Celeste et al., 2023). Whilst this may not be a surprising connection, combining quantitative inference with qualitative data surrounding poverty and sanitation can enhance understanding of the underlying factors influencing progress to SDG6.

2.4.2.2 Modelling future predictions

Arguably, one the most valuable applications of mathematical modelling SDG6 is the use of mathematical models to predict future trends and scenarios. Understanding of the potential of mathematical models to serve such a purpose was perhaps best characterised through the

COVID 19 pandemic in which mathematical modelling of infectious disease epidemiology was used to inform policy making (Khoshnaw et al., 2020).

Example: Population growth to understand water and sanitation demand

Modelling has been used to explore future scenarios of population growth, providing a conceptual framework for multiple scenarios of population growth and change that is central to understanding progress to all SDGs. One example of this is the case of the Shared Socioeconomic Pathways (SSPs), these provide possible trajectories of population change and socioeconomic development, Figures 2.6 and 2.7 (Riahi et al., 2017; LC and Lutz, 2017). The pathways outline 5 possible scenarios of population change. The pathways are typically coupled with associated scenarios of land use and greenhouse gas emissions to paint a holistic picture of societal development (Kebede et al., 2018; Riahi et al., 2017.). Applying such a scenario-based format not only provides insight into possible future patterns of development, predicting population, education and economic development, Figure 2.7 but also provides a system to handle the significant uncertainty surrounding population and social change.

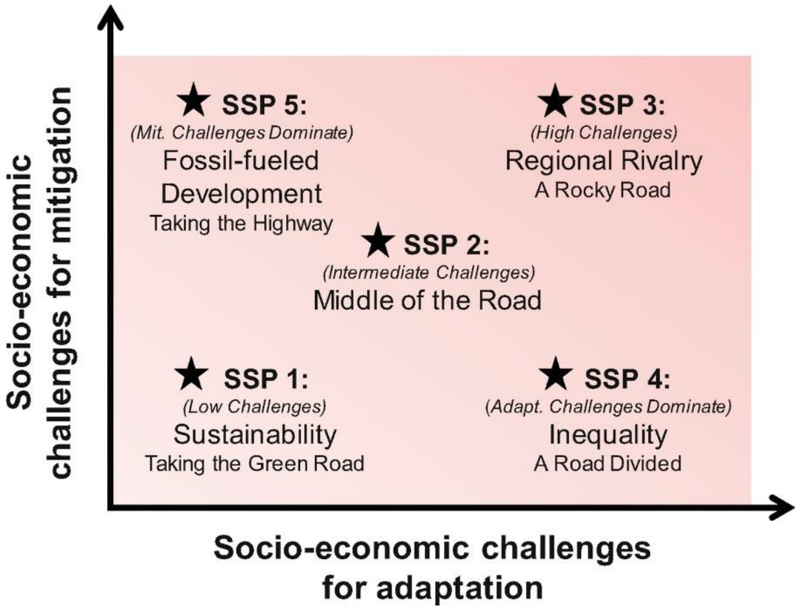


Figure 2.6: The narratives of the 5 SSPs, source O'Neill et al., 2017.

This is invaluable in the understanding of future water and sanitation demand which is needed to ensure consistent progress to SDG6. Forecasts of future demand are important in developing sanitation and water infrastructure as such projects may take years to develop, reliable predictions of future demand are therefore required to ensure that appropriate infrastructure can be developed in advance. For example, evaluating multiple SSP-RCP scenarios to consider multiple scenarios of population change and economic development in Pakistan's Rechna Doab region, Alizadeh *et al*., 2022 predicted an average growth in groundwater demand of 29.06% by 2030, compared to 2022 (Alizadeh et al., 2022). By evaluating multiple scenarios, uncertainty in population change and economic development was accounted for, highlighting a growing challenge of groundwater depletion in all cases, and evidencing the need for policy directly addressing this concern (Alizadeh et al., 2022).

Another example of how population growth projections are critical to developing understanding and solutions within WaSH is the development of appropriate sewerage systems. Öberg *et al.,* 2020 identified that, of the 60 fastest-growing cities in the world, most would need to construct sewer systems at a rate that is 10 -50 times higher than the highest rate of any sewage construction currently being undertaken (Öberg et al., 2020). This raises critical awareness of the need to reconsider a growing sanitation crisis and emphasises the requirement for long-term investment into sanitation development.

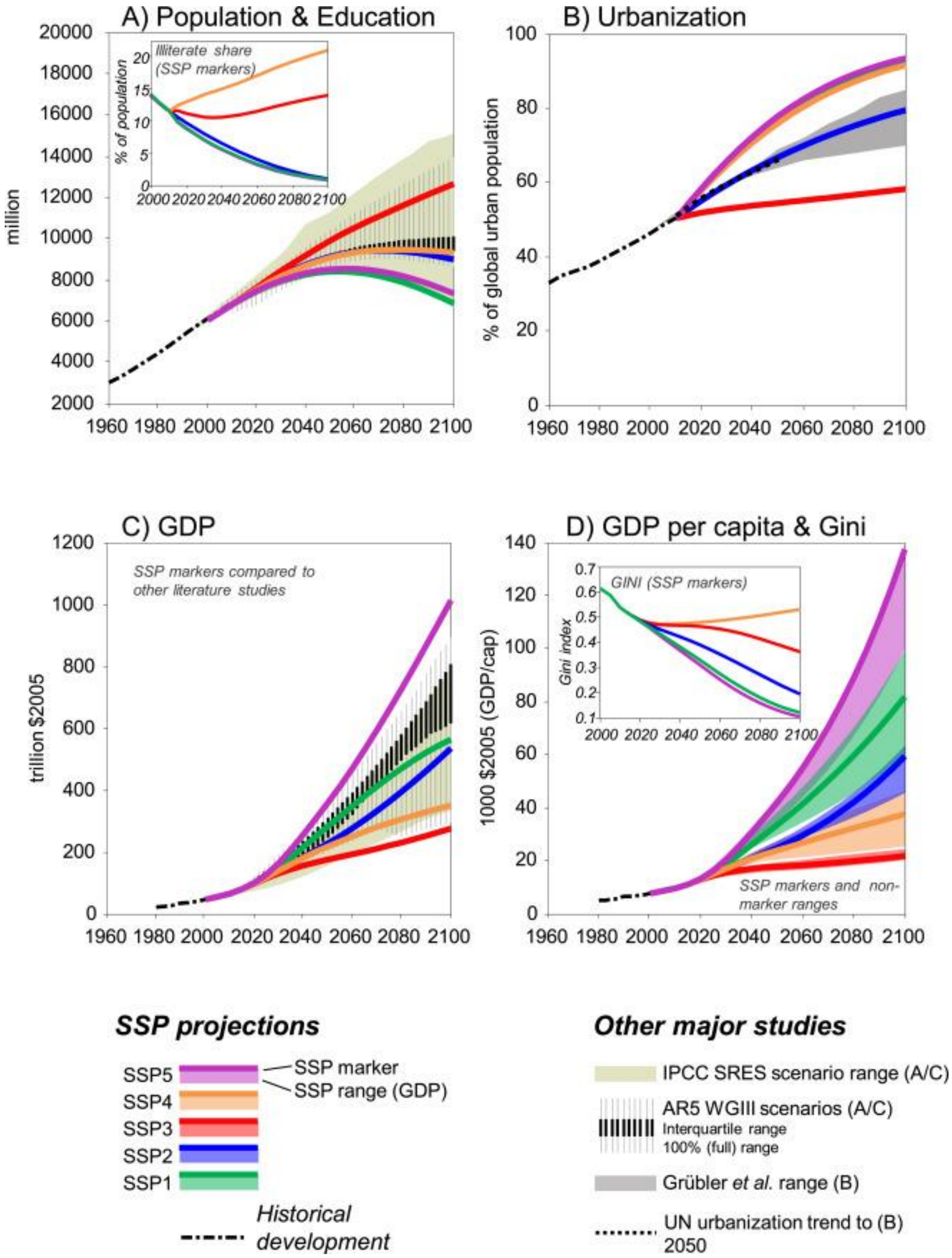


Figure 2.7: How the 5 SSP pathways intersect with different socioeconomic parameters of population, education, urbanisation, and GDP. Source Riahi et al., 2017.

2.4.3 Hydrological modelling

Within the sphere of water resource management, hydrological models are widely used to develop both current and future understanding (Chen et al., 2021). Hydrological models can commonly be considered in 4 classes: Metric models, Conceptual models, Physics-based models, and Hybrid models. Metric models are the simplest form of model, they are based on statistical relationships such as regression models and time series models. These do not explain physical processes but can use statistical analysis to predict future trends. Conceptual models use representations of storage of water within aspects of the water cycle (e.g. groundwater, surface water, and soil moisture), and simulate how water moves between these aspects. Movement between classes is represented by mathematical equations. Examples include the Soil and Water Assessment Tool (SWAT) (Akoko et al., 2021). Physics-Based models represent hydrological processes based on physical processes and laws, an example is the HydroGeoSphere model. Finally, hybrid models combine multiple elements of the above models. (Nesru, 2023; Yoosefdoost et al., 2022). Different hydrological models may use varying techniques to capture an aspect of the water cycle (for example focusing on groundwater or surface water models) to paint a holistic picture of the water cycle for a specific region. Hydrological models are utilised in both representing real-world systems to develop understanding as well as to predict future patterns and trends.

2.4.2.3 Hydrological modelling of Malawi's water resources

Within Malawi, hydrological models have been used to explore current water resources and enhance understanding (Calder et al., 1995; Lyons et al., 2011; Sehatzadeh, 2011; Sehatzadeh et al., 2017) as well as predict future water resources under differing scenarios (Bhave et al., 2020). Such models have typically focused on surface water (Bhave et al., 2020; Calder et al., 1995; Drayton, 1984; Neuland, 1984) or have been confined to water balance methods (Kumambala, 2010; Lyons et al., 2011; Shela, 2000) which have provided limited insights into comprehensive water resource management, especially concerning groundwater. Existing groundwater-specific modelling effort have primarily focused on the sub-catchment level

(Sehatzadeh, 2011). The only currently available estimate of Malawi's groundwater resources estimates Malawi's water resources between 96.7 and 1,108 km^3 (Kalin et al., 2022) presenting significant uncertainty in understanding the amount of groundwater within Malawi and future security of the resource. The large range of this estimate, beyond embedding significant uncertainty in understanding Malawi's current water resources, limits appropriate management and planning of groundwater security.

2.5 Knowledge gaps

This thesis addresses several knowledge gaps identified in Malawi's path to SDG6.

Incomplete Understanding of Water Scarcity: Due to inadequate infrastructure and a lack of comprehensive groundwater modelling, the understanding of groundwater resources in Malawi remains limited (Kalin, 2022). This results in significant uncertainty regarding the extent of groundwater availability and its future sustainability as a vital resource. In addition, the interconnectedness between groundwater and surface water systems adds complexity to the overall understanding of water resources management (Kelly et al., 2019). Whilst the interconnection between rivers and groundwater has been highlighted, with most river flow coming from baseflow (Kelly et al., 2019), there is currently limited understanding of the role of groundwater for other surface water availability, particularly lakes.

Uncertain drivers of water quality: Poor drinking water quality presents a critical threat to SDG6. The majority of the population currently access drinking water that is contaminated with *E.coli* (NSO, 2021). Yet the sources of groundwater contamination are not sufficiently understood making management challenging. In addition, the future risks of groundwater contamination are not clear, further work is needed to address how Malawi can safeguard water quality both now and in the future.

Variability in Sanitation and Hygiene Access Estimates: Malawi faces significant discrepancies in estimates of sanitation and hygiene access (Hinton et al., 2023). This lack of consensus hinders efforts to accurately assess progress and ensure uniform advancements in sanitation and hygiene provision across the country. Rapid demographic changes and the impacts of climate change are important to consider in understanding future sanitation provision and ensuring a *sustainable* path to SDG6. In meeting sanitation and hygiene targets under SDG6.2, the needs of women, girls and those in vulnerable situations needs to be at the forefront. For understanding of Malawi's path to SDG6 further work is needed to explore how the needs of women and girls are being met, or not, within the realm of sanitation and hygiene. Specifically, this involves the consideration of challenges in security and privacy within sanitation provision as well as appropriate menstrual hygiene management (MHM).

How to sustainably explore and promote solutions: Bridging the gap in knowledge involves identifying actionable solutions to address these challenges comprehensively. Implementing effective strategies that target various aspects of SDG6 will be instrumental in driving progress towards universal access to clean water and sanitation in Malawi.

2.6 Conclusion to this chapter

In conclusion, SDG6 in Malawi involves a complex and multifaceted nexus of water resource management and sanitation provision. Despite notable achievements, such as improvements in access to safe drinking water, significant challenges remain, including ensuring sustainable groundwater management and sanitation management under socioeconomic and climatic change. Addressing these challenges requires holistic approaches that integrate socioeconomic and environmental considerations. The next chapter explores some of the methods used within this thesis to address the knowledge gaps highlighted and build a better picture of how Malawi can work towards sustainable progress to SDG6.

Chapter 3: Methodology

“The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them.”

Sir William Bragg, date unknown

Chapter 3: Methodology

3.1 Introduction

This thesis employs a range of data sources and methods to explore challenges and solutions to SDG6 in Malawi. The thesis utilised data from a range of sources discussed in this chapter including national household surveys, infrastructure survey data, water quality assessments, measured hydrological and meteorological data, remote sensing, and semi-structured stakeholder interviews. A blend of quantitative and qualitative data sources was used to enhance understanding. Multiple methods were used for analysis, the role of predictive modelling was emphasised within this thesis and is further discussed in this chapter.

This chapter provides an overview of key methods used across the thesis. As this thesis is by publication, the specific approaches for individual pieces of work are explained in detail within the methods sections of each paper within the chapters.

3.2 Quantitative data

3.2.1 Household and population data

Household surveys provide a commonly used method to systematically gather information on socioeconomic factors and demographics. Information is collected through structured interviews or questionnaires administered to selected households, typically using a sampling framework to ensure representativeness. Data from multiple national household surveys for Malawi were used within this thesis including data from demographic and health surveys (DHS), Malaria Indicator Surveys (MIS), Census data, and UNICEF Multiple Indicator Cluster Surveys (MICS).

Demographic and Health Surveys (DHS) gather nationally representative data on multiple areas of population demographics and health (Boerma and Sommerfeld, 1993). The surveys cover topics such as fertility, maternal and child health, and malaria prevalence. They use stratified, multistage cluster sampling to randomly select representative households with data collected using standardised questionnaires and face-to-face interviews with individuals from selected households. Malaria Indicator Surveys (MIS) employ similar methodology to DHS surveys, providing some information on health and social data alongside malaria-specific metrics, including bed net coverage and usage, indoor residual spraying coverage, access to antimalarial treatment, and the populace's knowledge regarding malaria prevention and treatment (DHS Programme, 2016). Similarly, to DHS and MIS surveys, census data also employs household surveys to gather data on population and household characteristics. Unlike the DHS and MIS data, census efforts (which have typically occurred once a decade) assess every household within Malawi. Multiple Indicator Cluster Surveys (MICS), undertaken by UNICEF in partnership with national governments, also encompass a broad spectrum of topics relevant to child, maternal, and family well-being. MICS surveys cover areas including health, education, child protection, and nutrition, employing methodologies akin to DHS and MIS surveys. All these surveys provide information on sanitation and water as crucial household indicators.

Within this thesis, data from 5 DHS was used (conducted in 1992, 2000, 2004, 2010, and 2015/16), MIS (conducted in 2012 and 2014), Census data from 2018, 2 MIS (from 2012 and 2014) and MICS from 2020.

In addition to the national surveys, data from a 2019 CARE sanitation and hygiene survey of communities within two districts of Malawi previously declared open-defecation free was analysed. This data was collected in a similar method to DHS, MIS and MICS surveys, taking a representative cluster of households within the identified communities and conducting household surveys.

3.2.2 Infrastructure survey data

Water and Sanitation (WaSH) infrastructure is a central consideration in meeting the requirements of SDG6. Whilst many targets within SDG6 focus on the proportion of the population using WaSH infrastructure (JMP), with surveys typically conducted at a household level, there is limited monitoring of WaSH infrastructure itself (Kalin et al., 2019). Identification, and monitoring, of WaSH infrastructure is critical in consideration of infrastructure management practices and challenges.

An extensive survey of water and sanitation infrastructure was conducted by the Government of Malawi through the Scottish Government's Climate Justice Fund (CJF) from 2012-2021 (Kalin et al., 2019). As part of this, two surveys were conducted, one examining water infrastructure (surveying over 100,000 water-points) and one investigating sanitation infrastructure (inspecting over 200,000 sanitary facilities). Each survey mapped the location of infrastructure, examined its condition (based on specified criteria) and surveyed users to provide information on the construction, usage, and management of the facility. Both surveys were conducted in Chichewa or English by trained Government of Malawi staff members. Survey data, for both water and sanitation surveys, was quality controlled at the University of Strathclyde.

3.2.3 Water quality data

Alongside the demographic factors discussed above, the 2020 UNICEF MICS survey also evaluated water quality data (NSO, 2021). The survey was conducted by the Government of Malawi National Statistical Office in collaboration with UNICEF from December 2019 -August 2020 of 26,882 households in 1,111 clusters. Water quality testing was conducted at 2,818 waterpoints within the 1,111 clusters nationally. Georeferenced water quality data was provided by UNICEF Malawi. The data provides information on drinking water sources, including an evaluation of *E.coli* contamination of drinking water resources.

Groundwater quality data was also collected by the Government of Malawi through water quality testing of boreholes conducted when boreholes were drilled. Data was collected from 2,993 water-points nationally, providing information on measures of groundwater quality Ph, Electrical Conductivity, Total Dissolved Solids, Chloride, Sulphate, Nitrate, Fluoride, Iron, Manganese, and Calcium. Data was provided by the Government of Malawi, Department of Water Resources.

3.2.4 Meteorological and hydrological data

3.2.4.1 Measured meteorological and hydrological data

Precipitation and river flow data was supplied by the Government of Malawi, Department of Water Resources from meteorological stations and river gauges. Whilst precipitation and river discharge data were available for many stations nationally, with some data logs extending for more than 50 years, much of the data was incomplete with many records missing datapoints. Data which did not have sufficient contiguous monitoring was not utilised. Detailed information on the number of datapoints used and distribution is summarised within the relevant chapters.

3.2.4.2 Remote sensed data meteorological and hydrological data

Remote sensed data provides one method to overcome some of the challenges of incomplete meteorological and hydrological measured datasets. Remote sensed data can provide valuable insights into weather patterns, precipitation, temperature, evapotranspiration, and gravitational fields (used to assess total water storage). Satellites equipped with specialized sensors capture images and data across large geographic areas, allowing for comprehensive coverage and monitoring.

This thesis utilised several remotely sensed datasets to enhance understanding of climatic and meteorological variables in Malawi. Where available, multiple datasets were used. Precipitation estimates were obtained from the TRMM 3B42 (Adler et al., 2003; Huffman, 1997; Huffman, 2012; Huffman et al., 1997; Huffman et al., 2007; Hufman et al., 2001; Huffman et al., 1995). 5 evapotranspiration datasets were obtained from NASA GLDAS (Rodell et al., 2004), MODIS 500m (Running and Mu, 2015), Terraclimate (Abatzoglou et al., 2018), NASA SMAP (Reichle et al., 2022), and PML_V2 (Zhang et al., 2019; 2016; Gan et al., 2018). The Gravity Recovery and Climate Experiment (GRACE) satellites were used to estimate change in the total water storage of the basin by monitoring small changes in earth’s gravitational field due to changes in mass (from water storage) (Swenson, 2012; Landerer and Swenson, 2012; Swenson and Wahr, 2006).

All remote sensing datasets were open access and were accessed, visualised, and analysed through Google Earth Engine (Gorelick et al., 2017).

3.3 Quantitative data analysis

3.3.1.1 Geospatial analysis

Geographic Information (GIS) technology was used through this thesis to enhance the analysis of highly geospatial datasets. GIS was used throughout this thesis to generate, analyse, and visualise spatial data. Within this thesis, QGIS is utilised for spatial data processing (QGIS, 2024). QGIS was chosen for analysis as it is an open-source software, thereby enhancing the accessibility of the research methods presented. QGIS was used for the generation of some spatial data, such as shapefiles of the extents of wetlands and areas of flooding where shapefiles were unavailable. In addition, QGIS was used extensively for data visualisation and the generation of figures.

Further spatial data analysis (including raster analysis) was conducted in the programming language R through dedicated spatial analysis packages including Raster, sf, sp, rgdal, and rgeos (R Core Team, 2024).

3.3.1.2 Predictive modelling methods

Predictive modelling is integral to the thesis's aim to explore both current and future risks to SDG6. The modelling techniques employed in this thesis are geared towards understanding patterns, trends, and potential future scenarios related to water, sanitation, and hygiene in Malawi.

Within this work, statistical analysis, modelling, and visualisation was conducted primarily through the statistical analysis software, R (R Core Team, 2024).

3.3.1.2.1 Linear modelling

Linear modelling is a statistical approach utilised to explore the relationship between a dependent variable and one or more independent variables, operating under the assumption that this relationship can be represented by a linear equation. As a simple type of analysis, it is one of the most commonly used predictive modelling techniques with many variants, each offering specific insights.

Simple linear regression, and generalised linear regression (or generalised linear modelling) are common variants of linear models and were used within this thesis. Simple linear regression is used to model the relationship between two variables. In simple linear regression, the goal is to estimate the slope and intercept of the regression line that best fits the observed data points, minimizing the sum of squared differences between the observed and predicted values. Within this thesis simple linear regression was used to examine and forecast future trends.

Generalised linear regression (or generalized linear modelling) extends the principles of simple linear regression to accommodate more complex relationships between variables and handle non-normally distributed outcome variables (Liu, 2016). Unlike simple linear regression, which assumes that the response variable follows a normal distribution, generalised linear regression allows for response variables that follow other distributions, such as binomial, poisson, or gamma distributions.

Within this thesis GLM models were used to examine multiple variables simultaneously to identify the relative importance of each predictor variable in explaining variability in an outcome variable. The coefficients associated with each predictor used to assess the strength and direction of their effects on the response variable. Other variables are controlled within the model, to provide comparison of the relative importance of multiple predictors.

GLMs can be extended further to Generalised Linear Mixed Models (GLMMs) which incorporate random and fixed effects into the model structure, allowing for the analysis of clustered or hierarchical data where observations are not independent (Rabe-Hesketh and Skrondal, 2008; Muschelli et al., 2014)). Within this thesis GLMMs were used where additional independent variables have effects on the dependent variables but are not independent variables of interest. GLMMs are used to identify which variables have the strongest impact on outcome variables.

Further information on model assumptions and verification is provided in detail within specific papers in chapters 4-7.

3.3.1.2.2 Random forest

Random Forest provides an alternative method of predictive modelling, also handling complex relationships between predictor variables and dependent variables (Louppe, 2014). Unlike linear modelling, random forests involve the construction of multiple decision trees. Each tree is built using a random subset of the training data and a random subset of the features, multiple trees are constructed with different subsets of features to determine which features are most important.

Within this thesis random forest modelling was used for predicting spatial patterns of a variable of interest. Whilst the random forest modelling does provide insight into the relative importance of multiple predictor variables used within random forest models, it does not provide general information of the significance of the variable overall and therefore has limited information for determining the relative importance of multiple predictor variables (Ishwaran, 2007).

3.3.1.2.3 Hydrological modelling

Hydrological modelling applies multiple methods to simulate hydrological events and create representations of water resources. Within this thesis, the global hydrological model, the Community Water Model (CWatM) was used for hydrological modelling (Burek et al., 2020). The model features multiple inputs and outputs, notably representing water demand. Further detail of the hydrological modelling process is provided within the specific methods sub-chapters of papers within chapter 4.

The three-dimensional finite-difference groundwater flow model MODFLOW was also used within this thesis due to its capacity to offer enhanced modelling of groundwater dynaMICS (MODFLOW 6), an area which is often limited in global hydrological models (Guillaumot et al., 2022). A coupled model of the CWatM and MODFLOW was used (Guillaumot et al., 2022) to enable holistic water resource modelling. The model was coded in the programming language python (Van Rossum and Drake, 1995) with analysis of model outputs conducted in R (R Core Team, 2024).

3.4 Qualitative data collection and analysis

In addition to quantitative data, qualitative data was used to enhance understanding of every aspect of SDG6 explored in this thesis. Some of the methods used to collect and analyse qualitative data are summarised below.

3.4.1 Qualitative survey data

The CJF surveys discussed above (Kalin et al., 2019), not only gathered quantitative data surrounding water and sanitation infrastructure in Malawi, but also provided qualitative data, particularly regarding attitudes towards water-point and sanitary facility management. Participants were asked to respond to set questions and trained Government of Malawi enumerators listed whether responses fell within pre-determined categories/ themes, listening all areas mentioned and deemed relevant. If parts of a response did not fit within a listed category, it was recorded as ‘other’ and a written synopsis was given.

Qualitative content analysis was used to analyse the gathered qualitative data, grouping responses into thematic clusters to provide an overview of commonly given responses. All studies followed ethical guidance from the Government of Malawi and informed consent was obtained for data collection.

3.4.2 Workshop responses

Alongside the quantitative responses collected, the CARE sanitation and hygiene survey (2019) also conducted stakeholder workshops in the selected communities, to further gauge attitudes to sanitation and hygiene challenges. Public attitudes and other insights from these workshops, alongside specific quotes, were used to aid the interpretation of quantitative findings. The study followed guidelines from the Government of Malawi Ethics Committee and informed consent was obtained from all participants.

3.4.3 Semi-structured stakeholder interviews

Semi-structured stakeholder interviews are another qualitative research method that was used to gather insights and perspectives from key individuals. The interviews involved a flexible framework with predetermined questions but allowing for open-ended discussion to gather insight and perspectives in a dynamic way.

Semi-structures stakeholder interviews were used to develop understanding of topic area and inform the areas of research presented within this thesis. A series of stakeholder interviews with politicians, policy makers, NGOs, businesses, and communities were conducted in October 2022. The knowledge gaps identified by key stakeholders, were used alongside literature identified knowledge gaps to inform and guide the focus areas of research. Emphasising close stakeholder engagement ensured the work presented in this thesis is rooted in stakeholder needs. Ethical approval was obtained through the James Hutton Institute Ethics Committee.

Alongside the broad-based stakeholder engagement mentioned, a series of specific semi-structured stakeholder interviews were conducted in July 2023 to inform understanding of Malawi's water resources (discussed in detail in Chapter 4). Ethical approval was sought from the IIASA ethical committee and informed consent was obtained from all participants.

3.5 Ethics

Where relevant, ethical approval was sought for all aspects of the research conducted within this thesis. University of Strathclyde guidelines on ethical approval were followed to determine where ethical approval was required. Ethical approval was sought from the James Hutton Institute Ethics board for a series of stakeholder interviews gathering views of priorities and concerns in SDG6. In addition, ethical approval from the James Hutton Institute was granted for a series of interviews with communities practising borehole-garden permaculture to develop understanding the adoption of the technique. Ethical approval was provided by the IIASA ethics committee for a series of stakeholder interviews to develop conceptual understanding of Malawi's water management and inform the development of a national model of water resources. Ethical approval is detailed within each piece of work presented. All participants provided informed consent and all data was anonymised.

Where ethical approval was not required as the information was factual, as in the case of the CJF survey, or gathered by a third party, as in the case of the CARE International surveys, all data followed guidance from the Government of Malawi Ethics Committee.

Further information on ethical approval is provided in Appendix C.

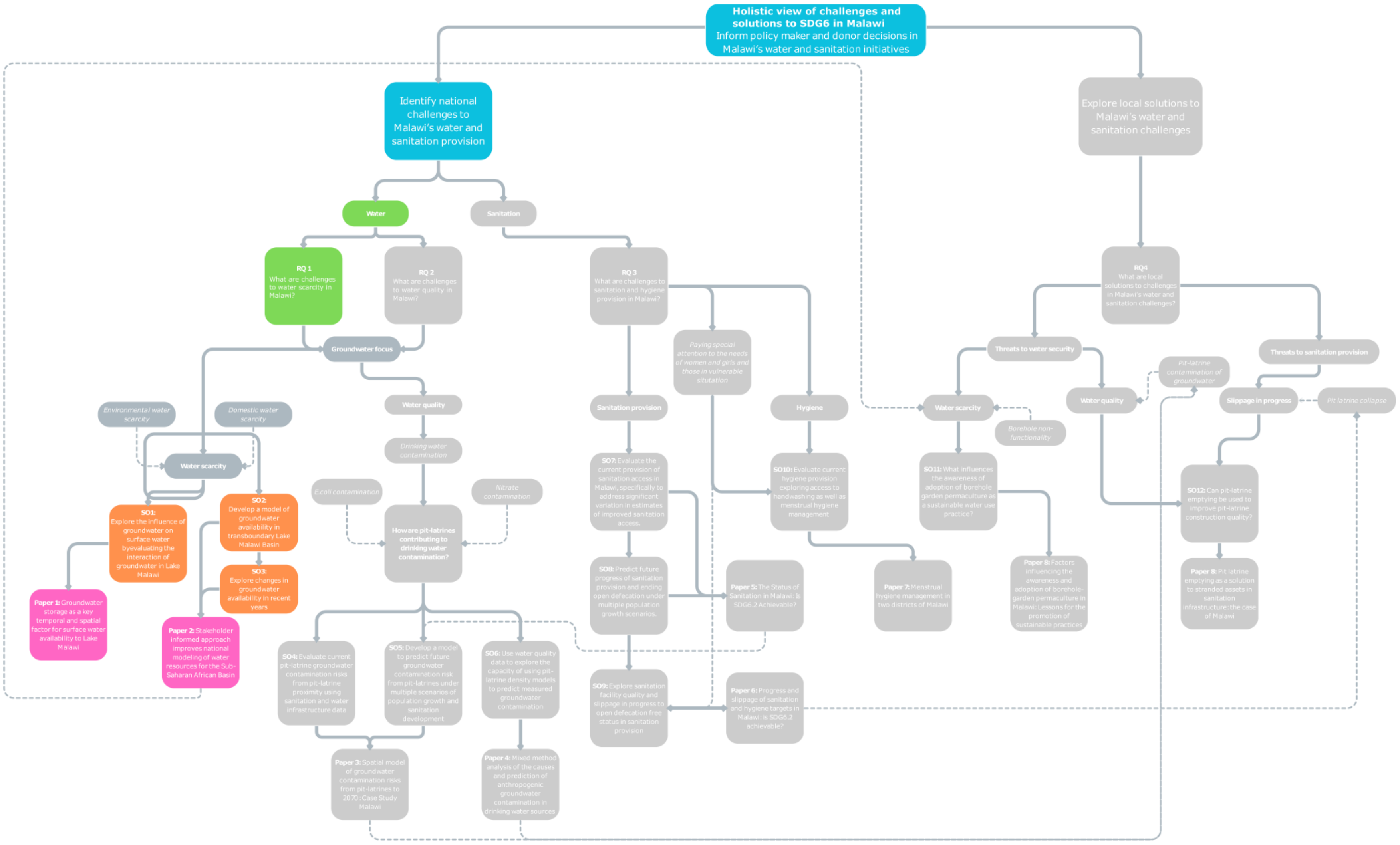
In this work, researcher positionality is a critical consideration, particularly given the notable differences in socioeconomic and cultural contexts between the researcher's background in the UK and the research context of Malawi. As a white, affluent researcher based in Scotland, the researcher brings a set of inherent biases, privileges, and perspectives that may not fully align with the experiences and realities of many communities in Malawi. To address this, the research philosophy adopted for this thesis prioritises a stakeholder centred approach, placing the concerns and insights identified by key stakeholders in Malawi at the forefront of the research process. By actively involving stakeholders throughout the research journey, from conceptualisation to implementation, the aim is to ensure that the research is grounded in the local context and that the findings are relevant, meaningful, and respectful of the community's perspectives and needs. This approach fosters collaboration, mutual understanding, and empowerment among all involved parties, ultimately enhancing the ethical integrity, credibility, and validity of the research outcomes.

Chapter 4: Challenges of water scarcity for SDG6

"Kuzama Kwa chitsime kumadziwika madzi akaphwera"

Chichewa expression

The depth of a well is appreciated when it runs dry


Holistic view of challenges and solutions to SDG6 in Malawi
Inform policy maker and donor decisions in Malawi's water and sanitation initiatives
Identify national challenges to Malawi's water and sanitation provision
Explore local solutions to Malawi's water and sanitation challenges
Water
Sanitation
RQ 1 What are challenges to water scarcity in Malawi?
RQ 2 What are challenges to water quality in Malawi?
RQ 3 What are challenges to sanitation and hygiene provision in Malawi?
RQ4 What are local solutions to challenges in Malawi's water and sanitation challenges?
Groundwater focus
Environmental water scarcity
Domestic water scarcity
Water scarcity
SO1: Explore the influence of groundwater on surface water byevaluating the interaction of groundwater in Lake Malawi
SO2: Develop a model of groundwater availability in transboundary Lake Malawi Basin
SO3: Explore changes in groundwater availability in recent years
Paper 1: Groundwater storage as a key temporal and spatial factor for surface water availability to Lake Malawi
Paper 2: Stakeholder informed approach improves national modeling of water resources for the Sub-Saharan African Basin
Water quality
Drinking water contamination
E.coli contamination
Nitrate contamination
How are pit-latrines contributing to drinking water contamination?
SO4: Evaluate current pit-latrine groundwater contamination risks from pit-latrine proximity using sanitation and water infrastructure data
SO5: Develop a model to predict future groundwater contamination risk from pit-latrines under multiple scenarios of population growth and sanitation development
SO6: Use water quality data to explore the capacity of using pit-latrine density models to predict measured groundwater contamination
Paper 3: Spatial model of groundwater contamination risks from pit-latrines to 2070: Case Study Malawi
Paper 4: Mixed method analysis of the causes and prediction of anthropogenic groundwater contamination in drinking water sources
Paying special attention to the needs of women and girls and those in vulnerable situtation
Sanitation provision
Hygiene
SO7: Evaluate the current provision of sanitation access in Malawi, specifically to address significant variation in estimates of improved sanitation access.
SO8: Predict future progress of sanitation provision and ending open defecation under multiple population growth scenarios.
SO9: Explore sanitation facility quality and slippage in progress to open defecation free status in sanitation provision
SO10: Evaluate current hygiene provision exploring access to handwashing as well as menstrual hygiene management
Paper 5: The Status of Sanitation in Malawi: Is SDG6.2 Achievable?
Paper 6: Progress and slippage of sanitation and hygiene targets in Malawi: is SDG6.2 achievable?
Paper 7: Menstrual hygiene management in two districts of Malawi
Threats to water security
Water scarcity
Borehole non-functionality
Water quality
Pit-latrine contamination of groundwater
Threats to sanitation provision
Slippage in progress
Pit latrine collapse
SO11: What influences the awareness of adoption of borehole garden permaculture as a sustainable water use practice?
SO12: Can pit-latrine emptying be used to improve pit-latrine construction quality?
Paper 8: Factors influencing the awareness and adoption of borehole-garden permaculture in Malawi: Lessons for the promotion of sustainable practices
Paper 8: Pit latrine emptying as a solution to stranded assets in sanitation infrastructure: the case of Malawi

Chapter 4: Challenges of Water Scarcity for SDG6

4.1 Introduction

Consideration of water security to achieve SDG6 and ensure ‘clean water and sanitation for all’ requires safeguarding both appropriate water quantity and quality. This chapter addresses challenges in water quantity for Malawi to reach SDG6, answering RQ1 “What are challenges to water scarcity in Malawi?”.

Malawi’s water resources are dominated by the presence of Lake Malawi (or Lake Nyasa), in both total water volume and rhetoric, giving the illusion of a water rich country. Yet despite the presence of the world’s fifth largest lake lying largely within its territory (Herdendorf, 1984), Malawi is classed as a water scarce country with renewable internal freshwater resources per capita of under 1000m^3 per year (Worldbank, 2024). Furthermore, Malawi is rapidly moving towards absolute water scarcity, under 500m^3 per capita per year, Figure 4.1. Under current rates of population growth (UN Population Projection, 2024) and assuming a constant value of total internal renewable water resources of 1.6 10^16 m^3 (Worldbank, 2024), Malawi is projected to reach absolute water scarcity by 2042.

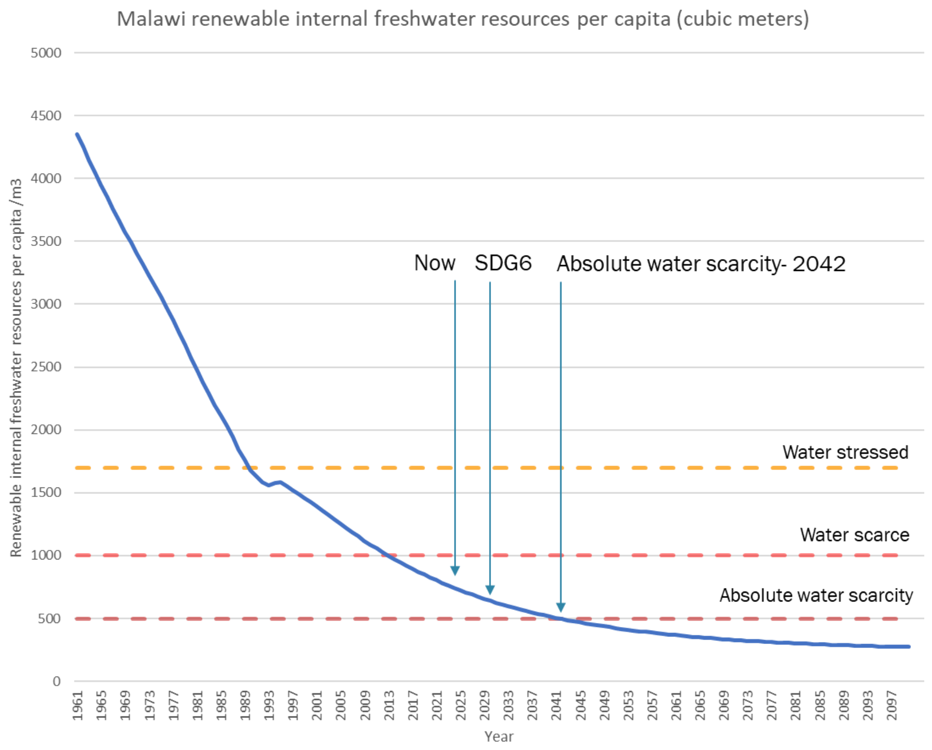


Figure 4.1: Renewable Internal Freshwater Resources (RIFR) per capita (m^3) for Malawi calculated as the total RIFR (Worldbank 2024) divided by population projection (UN, 2024), used as an indicator of water stress/ scarcity. A country is classed as water stressed if it has <1700m^3 RIFR/capita, water scarce at 1000m^3 or less and facing absolute water scarcity at <500 m^3 RIFR/capita. Under standard population growth (UN Population Projection, 2024), Malawi is forecast to reach absolute water scarcity by 2042.

Despite the presence of extensive surface water resources, groundwater is central to water security within Malawi; in rural areas, 82% of domestic, agricultural, and industrial water needs are supplied by groundwater (Chavula, 2012). In addition, groundwater has been shown to have significant interplay with surface water resources within Malawi, contributing substantially to river flow through baseflow (Kelly et al., 2019). Understanding water availability requires a holistic view of water resources, notably considering the connection between groundwater and surface water. This chapter answers RQ1 through achieving the specific objectives:

SO1: Explore the influence of groundwater on surface water by evaluating the interaction of groundwater on Lake Malawi

SO2: Develop a model of groundwater availability in transboundary Lake Malawi Basin

SO3: Explore changes in groundwater storage within the Lake Malawi Shire River Basin This chapter is formed of two papers submitted, or in draft for submission, to international peer-reviewed journals and listed below:

Paper 1

Kalin, R.M†., Hinton, R.G.K†, Riddel, L., Rivett, M., Mleta, P., Kanjaye, M., Kamutula, S., Wanangwa, G., Uka, Z., Ngongo, C. (In Prep). Groundwater Storage as a key temporal and spatial factor for surface water availability to Lake Malawi.

†: Joint first authorship

Author contribution:

Conceptualization (R.M.K., R.G.K.H, L.R, R.M, P.M, M.K., S.K, G.W, Z.U, C.N), data curation (R.M.K), formal analysis (R.G.K.H, R.M.K, L.R), investigation (R.G.K.H, R.M.K, L.R), methodology (R.G.K.H, R.M.K, L.R), validation (R.G.K.H, R.M.K), visualization (R.G.K.H, R.M.K), project administration (R.M.K), supervision (R.M.K), writing original draft (R.G.K.H, R.M.K), review and editing (R.M.K., R.G.K.H, L.R, R.M, P.M, M.K., S.K, G.W, Z.U, C.N

It should be noted that this paper has been written alongside co-author Robert Kalin to provide a conceptual framework and introduction to the importance of groundwater storage to the overall water resources of Malawi and to provide this thesis with an exploration of the time-based climate-change influences on water resources in the Lake Malawi Basin. It is deemed to be an appropriate introduction to the themes discussed within this chapter but it is not key to the overall body of research the Author presents as a dissertation.

The final version this paper builds on various work from the wider research group, with critical publications currently in peer review. For timely submission of this thesis and to present the contribution to this paper, an outline draft is provided here with expectation of submission in May 2024.

The body of research submitted follows this work.

Paper 2

Hinton, R.G.K., Smilovic, M., Fridman, D., Willaarts, B., Banda, L., Macleod, C. J. A., Troldborg, Kalin., R.M. (*Under review by co-authors*). Stakeholder informed approach improves national modelling of water resources for the Sub-Saharan African Basin. *Environmental Science and Technology.*

Author contribution:

Conceptualization (R.G.K.H, R.M.K, L.B.), data curation (R.G.K.H, M.S, D.F, W.B), formal analysis (R.G.K.H), investigation (R.G.K.H), methodology (R.G.K.H), validation (R.G.K.H), visualization (R.G.K.H), project administration (R.M.K), supervision (R.M.K, M.S, D.F, W.B, M.T., K.M), writing original draft (R.G.K.H), review and editing (R.G.K.H, R.M.K., M.S, D.F, W.B, C. J.A.M, M. T, M. K, L.B)

4.2 Groundwater storage as a key temporal and spatial factor for surface water availability to Lake Malawi

Disclaimer: This paper provides one aspect of the overarching conceptual framework for this thesis, but it is not key to the overall body of research the Author presents as a dissertation.

The final version this paper builds on various work from the wider research group, with critical publications currently in peer review. For timely submission of this thesis and to present the contribution to this paper, an outline draft is provided here with expectation of submission in May 2024.

The body of research submitted follows this work.

DRAFT VERSION FOR REBEKAH HINTON THESIS: SUBMISSION PLANNED AFTER REVISION BASED ON PUBLICATION OF BANDA LAKE MALAWI CATCHMENT PAPER ACCEPTED WITH REVISIONS APRIL 2024

Robert M. Kalin[1*] †, Rebekah Hinton[1] †, Lauren Riddel[2], Michael Rivett[2], Prince Mleta[3], Modesta Kanjaye[3], Sydney Kamutula[3], Gift Wanangwa[3], Zione Uka[3], and Cosmos Ngongo[4,]

[1] Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, UK Robert.Kalin@strath.ac.uk,
[2] University of Strathclyde, Glasgow, UK
[3] Ministry of Water and Sanitation, Government of Malawi, Lilongwe, Malawi
* Correspondence: Robert.Kalin@Strath.ac.uk

†: These authors equally contributed to this work

Abstract: Lake Malawi, one of Africa's Great Lakes, has a strong cyclic storage pattern. Lake levels, river flow and groundwater baseflow indexes were used to estimate the total groundwater to the lake. There is insufficient groundwater level monitoring to determine if there is a relationship between groundwater storage and lake levels, however a proxy relationship estimating changes in aquifer recharge was determined. In Malawi, groundwater base flow makes up c. 71.53% of total river discharge, 66.51% in the wet season and increasing to 91.84% during the dry season. River flow into Lake Malawi is estimated to be 357.06 m^3/s with base flow contributing 229.04 m^3/s. Given the changes in weather due to ENSO and climate change, decomposition analysis, Fourier transform, and generalised linear modelling are used to analyse the time-series relationship between groundwater storage and lake levels. This statistical analysis shows that there is a significant relationship with a 6 - 7 yearly lag attributed

to changing groundwater storage as a result of ENSO related rainfall patterns, and a strong correlation of lake levels with an 11 year lag between the two series attributed to the Solar cycle. Overall, groundwater is shown to be important to surface water in Malawi as it provides a substantive discharge to the Lake.

1. Introduction

Malawi is a landlocked country and surface water resources, including Lake Malawi, are key to the economic growth, food, and energy security of the country (Bhave et al., 2020; Hinton et al., 2021). Malawi has surface water and groundwater resources that are unevenly distributed and vary temporally and spatially. Much of Malawi's available surface water is found in Lake Malawi, with secondary storage in Lake Chilwa and smaller lakes and reservoirs (Kalin et al., 2022). Groundwater resources are contained in the low storage fractured / weathered saprolitic Pre-Cambrian Basement Complex Aquifer (BCA) across much of Malawi, in limited inter-granular units, and in higher yielding alluvial aquifers along river channels, the East African Rift System (EARS), the shores of Lake Malawi, Lake Chilwa, Lake Malombe, Lake Chiuta, and in the Upper and Lower Shire Valley (Kalin et al., 2022).

Supporting integrated water resources management (IWRM), the country's drainage system is divided into 17 major river catchments that define Water Resources Areas (WRAs), only two of which drain outside the Lake Malawi/Shire/Zambezi System and into Lake Chilwa and Lake Chiuta instead. WRAs are further subdivided by smaller catchments into 78 Water Resources Units (WRUs) (Kalin et al., 2022).

The quantity of surface water resources in Malawi, especially in rivers, is a result of bimodal rainfall patterns that produce rainfall as surface runoff during the rainy season (November to April), and on groundwater base flow to maintain discharge during the dry season (May – October) (Kelly et al., 2020). Water resources in Malawi are prone to drought – flood cycles resulting from climate variability related to the El Nino and Southern Oscillation (ENSO) phenomena; incidents of floods are a common occurrence during the rainy season (Sazib et al., 2020; Gibson et al., 2017), particularly in the districts of Salima, Karonga and Lower Shire Valley districts of Chikwawa and Nsanje due to shallow topographical relief.

Malawi is dependent on both surface water and groundwater resources, and these resources are under severe threat of depletion (quantity and quality) resulting from uncontrolled extraction, catchment degradation, unsustainable agriculture practices, point and non-point disposal of human and industrial effluents, increased human population growth and urbanization, and climate change effects (Kalin et al., 2022). Studies in other areas of the world have shown that over abstraction of groundwater has a direct impact in surface waters, reducing the base flow index (BFI) of rivers leading to a significant drop in the total discharge (Mukherjee et al, 2018).

Malawi is located within the EARS which strongly influences the topography and water resources. Rift valley escarpments run parallel with Lake Malawi and influence the drainage pattern of rivers in the north of Malawi (Kumambala, 2010; NHA, 2018). Rivers in the central region of Malawi drain into Lake Malawi however some rivers in the south drain into the Shire / Zambezi River System or Lake Chilwa. Rivers from Southwestern Tanzania and Northwest Mozambique also drain into Lake Chilwa. The topography of Malawi has notably higher elevations in the North of the country that exceed 2,000 mAOD (National Hydrogeological Atlas (NHA), 2018), the upland plateau (700 to 1300 mAOD) and Lake Malawi which has a surface elevation of c. 475 mAOD, and lower lying land in the south dominated by the Shire River catchment having an elevation of c. 500 m and the lower valley below 200 mAOD (Figure 1). The Mulanje Massive is a localized high elevation region of c. 3,000 m in the southeast near the border with Mozambique.

Lake Malawi is c. 579 km long and ranges between 25 and 80 km wide, with an area of 28,800 km^2 (Kumambala and Ervine, 2010). The mean depth is 292 m with a maximum depth of c. 705 m (Kumambala and Ervine, 2010). Lake Malawi's catchment covers an area of 97,740 km^2 with Malawi contributing 68%, Mozambique 6% and 26% of Tanzania (Kumambala and Ervine, 2010), Figure 1. Overall, it is the third largest lake in Africa (Kumambala and Ervine, 2010) and supports wildlife, fisheries, tourism, and other anthropogenic activities in all three countries (Yihdego and Pafford, 2016). The Shire River is the only outlet for Lake Malawi and has been controlled by the Liwonde (or Kamuzu) Barrage since 1948 (Kumambala and Ervine, 2010), with construction finishing in 1965 (Bhave et al., 2020). This barrage acts as a hydropower scheme and a series of hydroelectric generating facilities on the Shire providing over 90% of Malawi's electrical supply. The Shire River is a water supply for the conurbation of Blantyre and provides an irrigation system to the Lower Shire Valley (Sene et al, 2017). The main rivers supplying Lake Malawi are the Bua, South Rukuru, Dwangwa, and Linthipe in Malawi; the Ruhuhu and Kiwira in Tanzania; and the Songwe which runs along the border between north Malawi and Tanzania (Sene et al, 2017). There are also several smaller rivers from all three countries that feed the lake. In total, Malawi provides c. 43% of the total river inflow, 53% from Tanzania, and 4% from Mozambique (NHA, 2018).

Malawi's climate is classed as sub-tropical with two main seasons: the dry season and the wet season (NHA, 2018). The dry season is from May to October with the wet season occurring during November to April (Pike and Rimmington, 1965). Moisture for rainfall is transported via the Inter-Tropical Convergence Zone (NHA, 2018) and through periodic cyclonic storms that form in the Southwestern Indian Ocean basin. Topography influences the precipitation in Malawi with the upland plateau receiving the highest levels of rainfall semi-arid conditions occurring at lower elevations.

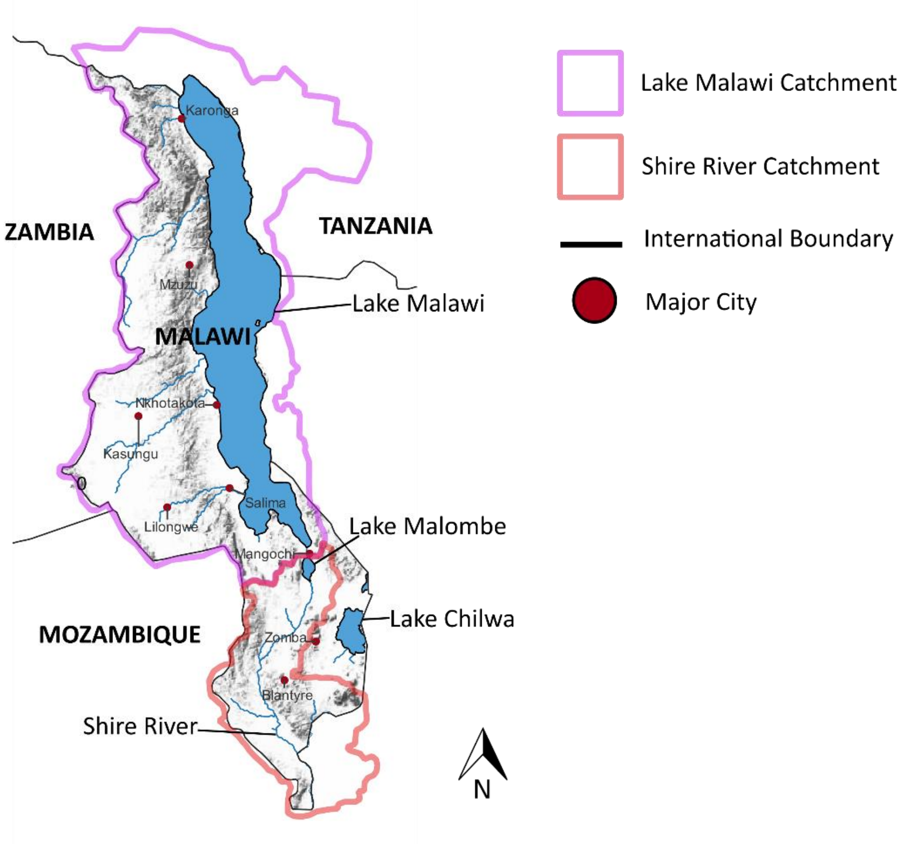


Figure 1. Lake Malawi Catchment showing the locations of major rivers and cities

1.1 Hydrogeology

The weathered basement aquifers occur mostly in the central region of Malawi, along the border with Zambia, and in the upland plateau (Kalin et al., 2022) (Figure 2). Chemical weathering of the metamorphic rocks has produced a layer of saprolite, made of quartz rich sand or weathered fine to coarse sand, which acts as an important water resource for rural communities (Smith-Carington & Chilton, 1983; Fraser et al, 2020). As the rock has a low primary porosity and low intergranular permeability, groundwater flow occurs in the weathered fractures of the geology (Smith-Carington & Chilton, 1983). The aquifer ranges c. 30 to 45 m thick with the thickness increasing towards fault zones and ranges from single layered aquifers to multi layers (Smith-Carington & Chilton, 1983; Fraser et al, 2018). A thick layer (5 to 20 m) of overlying clays partially confines the aquifers, while other aquifers are completely confined (Smith-Carington & Chilton, 1983; Fraser et al, 2018). The water table is located at the base of these clays (Smith-Carington & Chilton, 1983; Fraser et al, 2020). These aquifers have a transmissivity of c. 5 to 35 m^2/day and a hydraulic conductivity of 0.5 to 1.5 m/day (Chavula 2012; Fraser et al, 2020). They are relatively small and sporadic with a low productivity with boreholes having a yield of 1x10^{-4} to 1x10^{-3} m3/s and a storage coefficient of 5x10^{-3} to 1x10^{-2} (Chavula 2012; NHA, 2018). Due to the heterogeneous geology of this aquifer, the groundwater quality varies with mineralization ranging from 100 to 17,000 us/cm (NHA, 2018). Brackish water occurs in areas of high groundwater mineralization (NHA, 2018).

The fractured basement aquifer is extensive across Malawi, it has low productivity, and though it is considered one of the least important aquifers in Malawi, it is critical to local hand pump water supplies (Bradford, 1973). Storage is quite small, not widely connected, resulting in intermittent availability (NHA, 2018). Groundwater flow is located within the secondary porosity (fractures, folds, and faults) within the aquifer where there is high permeability (Smith-Carington & Chilton, 1983; Fraser et al, 2020). These aquifers have the same transmissivity and hydraulic conductivity as the weathered basement aquifers (Fraser et al, 2020). Boreholes within this aquifer also have a similar yield, with the most frequent yield being 5x10^{-4} m3/s (NHA, 2018). Overall, both the weathered and fractured basement aquifers have a low to moderate productivity (Fraser et al, 2020). As the geology of the fractured basement aquifers is resistant to weathering, very little mineralization has occurred within these aquifers resulting in good quality groundwater (Fraser et al, 2020). Some saline water is present, this is likely due to mineralization along fault zones within the unit (Rivett et al, 2018).

The main consolidated sediment aquifers are present in the Karoo sediments which are located along the southern and northern border. There is both primary and secondary porosity present, however, the primary porosity and granular permeability is smaller due to calcareous cements (Fraser et al, 2018). Secondary porosity provides the main flow paths in both the Karoo sediments and the Karoo igneous lithologies (Fraser et al, 2018). The transmissivity and yield vary throughout the aquifer, with lower values present in the calcareous sandstone (NHA, 2018). Aquifer testing shows the transmissivity in the confined sediments is c. 90 to 120 m^3/day and the yield is 346 m^3/day (NHA, 2018). It falls to 29 m^3/day and 25.9 m^3/day in the calcareous rocks (NHA, 2018). Similar to the basement aquifers, the Karoo sediment aquifers have a low to moderate productivity, although, the aquifer present in the igneous intrusion has a slightly higher productivity (Fraser et al, 2020). The water quality of the aquifers varies, with shallow aquifers having a mineralization of less than 1,000 us/cm (NHA, 2018). This increases to c. 2,000 us/cm in aquifers below 60 m and the water tends to be saline as a result of the evaporitic and calcareous cements (Monjerezi & Ngongondo, 2012; NHA, 2018). Water quality studies show that the groundwater present in the Karoo basalts has a good water quality and low concentrations of total dissolved solids (Monjerezi & Ngongondo, 2012). Due to the mineralogy of the basalts, less mineralization has occurred (Monjerezi & Ngongondo, 2012).

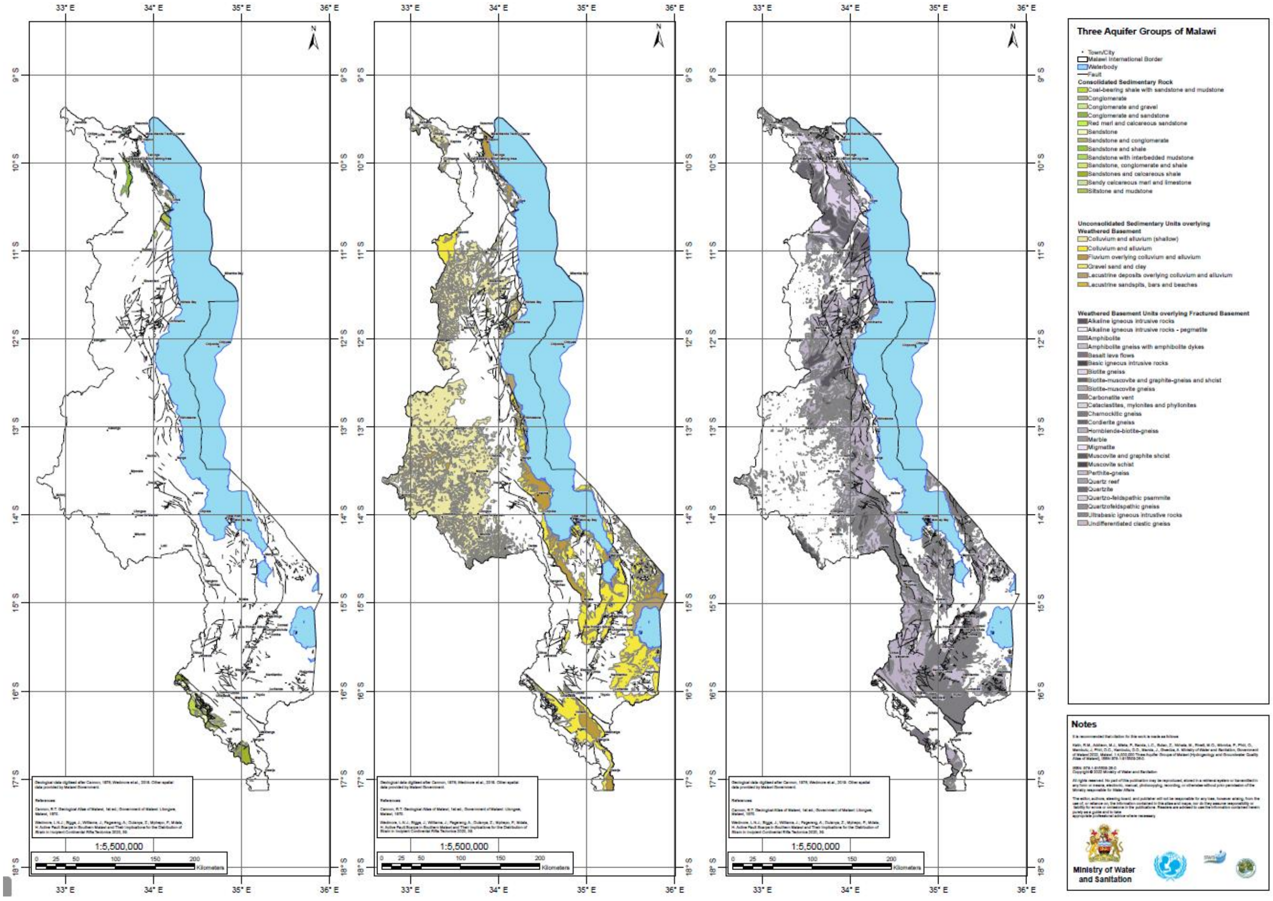


Figure 2. Hydrogeology Map of Malawi. After Kalin et al., 2022.

Unconsolidated alluvium aquifers make up a large portion of aquifers in Southern Malawi. The water table is typically shallower than that of the bedrock aquifers with the depth ranging from 5 to 10 m (Chavula, 2012) with and have a thickness of c. 40 to 150 m (Smith-Carrington and Chilton. 1983). Transmissivity and hydraulic conductivity are considerably higher than the older aquifers, with a transmissivity of 50 to 300 m^2/day and a hydraulic conductivity of 1 to 10 m/day (Chavula, 2012). Groundwater storage is also considerably higher at $1x10^{-2}$ to $5x10^{-2}$ (Chavula 2012). The majority of boreholes drilled into these aquifers have a yield of $2.x10^{-4}$ to $2.5x10^{-3}$ m^3/s (NHA, 2018), however some do have yields that excess $2x10^{-2}$ m^3/s (NHA, 2018). Layers of clay act as an aquitard in some areas of Malawi, confining the aquifer, with other aquifers being unconfined (Smith-Carington & Chilton, 1983). Overall, the alluvium aquifers have a high to very high productivity (Fraser et al, 2020). The water quality of these aquifers is mixed, with some areas having a brackish water and mineral concentrations of 9,000 us/cm (NHA, 2018).

1.2 Lake Malawi Water Balance

Several water balance models have been calculated for Lake Malawi (Healy et al, 2007; Kidd, 1983; Neuland, 1984; Drayton, 1984; Calder et al, 1995; Kumambala, 2010). The formative water balance models for Lake Malawi are summarised in Table 1. Kidd, 1983 and Neuland 1984, form two of these formative pieces of work in exploring Lake Malawi's water balance. The earliest model was based on 26 years of data with data from very few stations available and the main outcome was to model historic lake levels (Kidd, 1983). A similar time period was used within Neuland's model (1984) which found that rainfall with successive runoff can cause irregularly high lake levels. The precipitation relationship with the lake is summarized in equation 1 (Neuland, 1984):

R_L (t)=4.2+2.3sin((360^°)/104 t+214^°)+σE_D (t)

Equation 1: Rainfall relationship with Lake Malawi

Where RL is the precipitation over the lake, t is the time period in years, σ is the standard deviation and ED is the random component of the relationship with a distribution of 0,1 (Neuland, 1984; Kumambala, 2010).

Neuland (1984) also suggests that changes in land use around Lake Malawi will impact lake levels. In addition to water balancing, time series analysis, probability analysis and statistical analysis were used to predict future behaviors of the lake levels (Neuland, 1984). The water balance model completed by Drayton (1984) used the same time period and the main findings were that changes in precipitation resulted in high lake levels, and other factors such as changes in outflow are not significant enough to cause the changes (Drayton, 1984).

Table 1: Water balance estimated for previous studies (Kidd, 1983; Neuland, 1984; Drayton 1984; Kumambala, 2010)

	Kidd (1983)	**Neuland (1984)**	**Drayton (1984)**
Time Period	1954 to 1979	1954 to 1979	1953 to 1974
Precipitation (mm) Inflow	1414	1374	1350
River discharge (mm) Inflow	1000	693	693
Evaporation (mm) Outflow	1872	1605	1610
Discharge from lake (mm) Outflow	418	404	334
Change in Storage	+112	+58	+59

The time period examined by all three models was not long enough to definitively state the hydrological relations between inflows, outflows and changes in lake level. None of the models factor in potential inflows and outflows from groundwater from the lake or the importance of groundwater to the river discharge into the lake. The models also examine the lake during a period when lake levels were increasing. Therefore, the findings cannot be applied to periods of where the lake levels are declining. Climate change will also have influences on the volumes of precipitation and evaporation, consequently these models cannot be used within sustainable management plans.

A more recent water balance study was completed by Calder et al (1995) that examined how the change in land use affects Lake Malawi's water levels, using rainfall and lake level data from 1896 to 1994 (Calder et al, 1995). It agreed with the findings of Drayton's (1984) where changes in precipitation is the main factor influencing lake levels (Calder et al, 1995). Between 1967 and 1990, there is a decrease of 13% in forest cover within the catchment leading to an increase in surface runoff which is consistent with the findings of Neuland's (1994) model (Calder et al, 1995; Kumambala, 2010).

Calder et al (1995) suggests that there is a lag of one month between water flowing into the lake and outflows from the lake. The water balance model from Calder et al (1995):

ΔS(t)=R_L (t)+R_S(in) (t)-E(t)-R_S(out) (t-1)

Equation 2: Water balance with lag Calder et al., 1995

The most recent water balance model was completed by Kumambala (2010). This model uses the same rainfall and river flow data for 1976 to 1990 (Kumambala, 2010). The water balance model from Kumambala, (2010) is:

ΔL(t)=R_L (t)-E(t)+((Q_in (t)-Q_((out)) (t))/A_L)

Equation 3: Water balance model equation Kumambala, 2010.

L_Est (t)=L_Obs (t-1)+ΔL(t)

Equation 4: Lake level estimation model Kumambala, 2010

Where ΔL(t) is the change in lake level over the time period analysed, Qin(t) and Qout(t) representing inflows and outflows and AL is the surface area of the lake (Kumambala, 2010).

While there is a high correlation between predicted lake levels and historic observed lake levels, r^2 of 0.98 using a Nash-Sutcliffe correlation, modelling future levels of the lake becomes problematic (Kumambala, 2010; Kumambala and Ervine, 2010). This is potentially due to groundwater storage and the importance of the baseflow component to rivers that was not considered within any previous model (Kelly et al., 2020).

1.3 Groundwater Storage

Previous studies investigated groundwater storage in Malawi focused on the basement aquifers (Robins et al, 2013). The storage within these aquifers is shown to be different for each water resource area (WRA), highlighting the heterogeneous nature of the aquifers. Robin et al (2013) estimates a water balance for these aquifers based on estimated volumes of groundwater storage and abstraction showing that several WRAs have a negative balance indicating that groundwater resources are being depleted.

Rainfall is the source of groundwater recharge within Malawi. Kelly et al 2020 (Kelly et al., 2020) showed that base flow provides a substantial source of river flow in Malawi. Groundwater recharge mechanisms are complex and therefore groundwater levels and flow to rivers may not immediately react to climate changes (Tudhope et al, 2001), it is therefore important to consider this hysteresis and evaluate groundwater storage and resulting baseflow variability related to various lag periods on the impact of surface water storage (e.g. Lake Malawi). ENSO (3 to 5 year periods) and sunspot cycles (11/22 year periods) may therefore contribute to longer-term changes in groundwater storage in Malawi. Given groundwater contributes to the majority of river discharge in Malawi, this work was undertaken to determine if there is a signal of these processes within the water level data for Lake Malawi. Specifically, this work addresses the research question: RQ1) What are the seasonal patterns of Lake Malawi Level change? RQ2) What influence does groundwater have on Lake Malawi water storage?

2. Materials and Methods

River data from 68 river gauges (see supplementary information) located in Malawi was provided by the Surface Water Division of the Department of Water Recourses of Malawi. There was no data available for gauging stations on rivers within water resource areas (WRA) 10, 12 and 13, hence they are not included. From this data, Kelly (2020) calculated the daily flow for each station with the period of data recorded for each station. Monthly and yearly averages were calculated for each river (see Supplementary information). The data was used to determine mean monthly and annual flows.

BFI values calculated by Kelly et al (2020) (supplementary information) were used to allocate the base flow and surface flow components of the monthly and annual average flows for each station for all the recorded data summarized into average values for each calendar month alongside the total average annual flow. The rivers that discharged directly into Lake Malawi were used to estimate the volume of inflow from groundwater to Lake Malawi.

National rainfall data for 42 weather stations in Malawi was provided by the Malawian Government. Monthly rainfall was calculated for individual stations and the national annual average (supplementary information) for 1949 to 2016. Only stations providing complete datasets were used to calculate average rainfall. Annual precipitation data for the gauging stations was verified to confirm that it was representative of average precipitation over the whole Lake Malawi Shire River Basin (LMSRB) for the period 1998-2011. The locations of gauging stations and the LMSRB basin is shown in Figure 1. Average precipitation estimates for the LMSRB was obtained from remote sensing daily precipitation estimates were obtained from the TRMM 3B42 (Huffman, 1997; Huffman, 2012; Huffman et al., 1997; Huffman et al., 2007; Hufman et al., 2001; Huffman et al., 1995). The average precipitation estimate for remote sensing and gauging stations were compared by calculating the Kling-Gupta Efficiency (KGE), equation 2.1 (Acharya et al., 2019). The KGE is a commonly used measure of model fit in hydrological models, including evaluating precipitation data, Acharya et al., 2019, and is calculated using equation 5 (Gupta et al., 2009). Models with KGE values between -0.41 and 1 are typically considered to have reasonable performance with higher KGE values indicating better fit (Knoben et al., 2019).

$$KGE = 1 - \sqrt{(r-1)^2 + (\frac{\mu_s}{\mu_o} - 1)^2 + (\frac{\sigma_s/\mu_s}{\sigma_o/\mu_o} - 1)^2}$$

Equation 5: Kling-Gupta Efficiency. Where r is the pearson coefficient, $\mu_s$is the mean of the simulated time series, μ_s is the mean of the observed time series, σ_s is the standard deviation of the simulated data, and $\sigma_o$is the standard deviation of the observed data.

To evaluate the impact of solar cycles on water resources, we also evaluated periodicity in evapotranspiration using monthly remote sensing estimates of evapotranspiration from 1958-2022. Average evapotranspiration estimates for the LMSRB were obtained from Google Earth Engine (Gorelick et al., 2017) using TerraClimate evapotranspiration estimates (Abatzoglou et al., 2018). Sources of data are summarised in Table 2.

Groundwater level monitoring is in its infancy in Malawi with the earliest groundwater monitoring data from 2009 and limited geographical representation (Kalin et al., 2022). As such, there is not sufficient data to determine if a correlation exists between groundwater storage and lake levels. Banks et al (in press) found a mean age of 36 years for shallow groundwater in Malawi, and therefore short period variation in recharge volumes are highly likely to influence variation of the base flow component to rivers. Precipitation variability with lag-periods were used as a proxy connection between groundwater storage and Lake Malawi's rate of decline during the dry season. Precipitation was investigated as the average precipitation over 3, 6 and 12 month periods with the relationship to lake level change investigated with no lag as well as lag periods of 1-15 years.

Table 2: Sources of data for precipitation, evapotranspiration, Lake/ river outflow, and Lake Level

Data	Source	Time period
Precipitation	Gauging stations	1949-2017
Precipitation	Remote sensing TRMM 3B42	1998-2011
Evapotranspiration	Remote sensing Terraclimate ET	1958-2022
Lake/River outflow	Government of Malawi	1948-2012
Lake Level	Government of Malawi	1900-2016

Periodicity in rainfall and evapotranspiration has been observed within Malawi and is noted to inform interpretation. Nicholsen and Entekhabi (1986) found that there was a 5 to 6.3 year periodicity in rainfall present in Malawi due to the ENSO. In this study, 7 years is chosen as it is the maximum length of the ENSO cycle (Tudhope et al, 2001). Kumbuyo et al (2014) found that there are two rainfall zones present over Lake Malawi: one in the north and one in the south of the lake. Studies show that the rainfall periodicity in these zones are 13.64 and 10.06 years respectively (Kumbuyo et al, 2014). The 11 year lag period is considered to be the length of a sunspot cycle (Schove, 1955).

2.2 Rate of Lake Level change

The rate of Lake Level change was evaluated to investigate drivers of Lake Storage change. Conceptual controls for the regression in lake levels and the slope of the regression are depicted in Figure 3 with changes in GW baseflow and evaporation being the main factors.

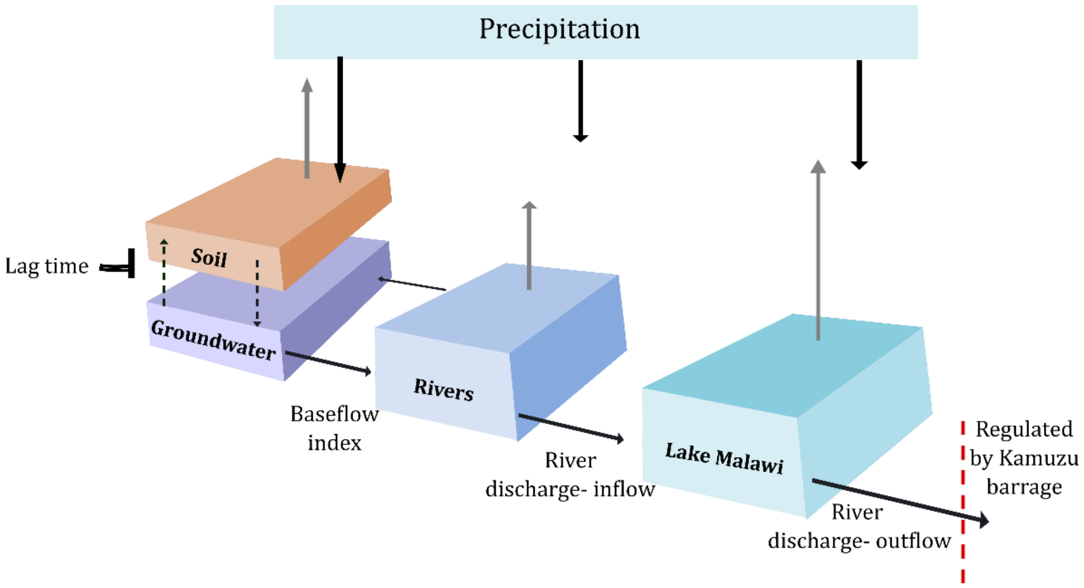


Figure 3. Conceptual model of water balance for Lake Malawi.

The rate of Lake Level Change was calculated by fitting a Local Polynomial Regression model (Cleveland and Devlin, 1988) to Lake Level data using the loess() function under the stats package in R (R Core Team, 2024). The method is outlined in Cleveland et al., 1992 (Cleveland et al., 1992). Multiple degrees of smoothing were investigated to find the best fit. The rate of Lake Level Change was calculated using the diff() function in the base package in R. The change in Lake Level was calculated for each month.

2.3 Periodicity of Lake Level change

The stationarity of Lake Level Change was calculated to confirm that it met the assumption of stationarity using the Augmented Dickey-Fuller test (Fuller, 1996) using the adf.test() function in the package aTSA in base R.

Interannual patterns of lake level change were investigated by calculating the annual moving average Lake Level Change This was calculated using the ma() function using the forecast package in base R. Seasonal trends in the annual moving average of Lake Level Change were extracted using seasonal decomposition of time series by local polynomial regression (Cleveland et al., 1990) using the decompose() function under the stats package in base R.

Figure 4 shows the theoretical decomposition of Lake Level change showing the major drivers of lake level change according to the time of year and wet/dry season. The rate of decline is of particular importance and is shown.

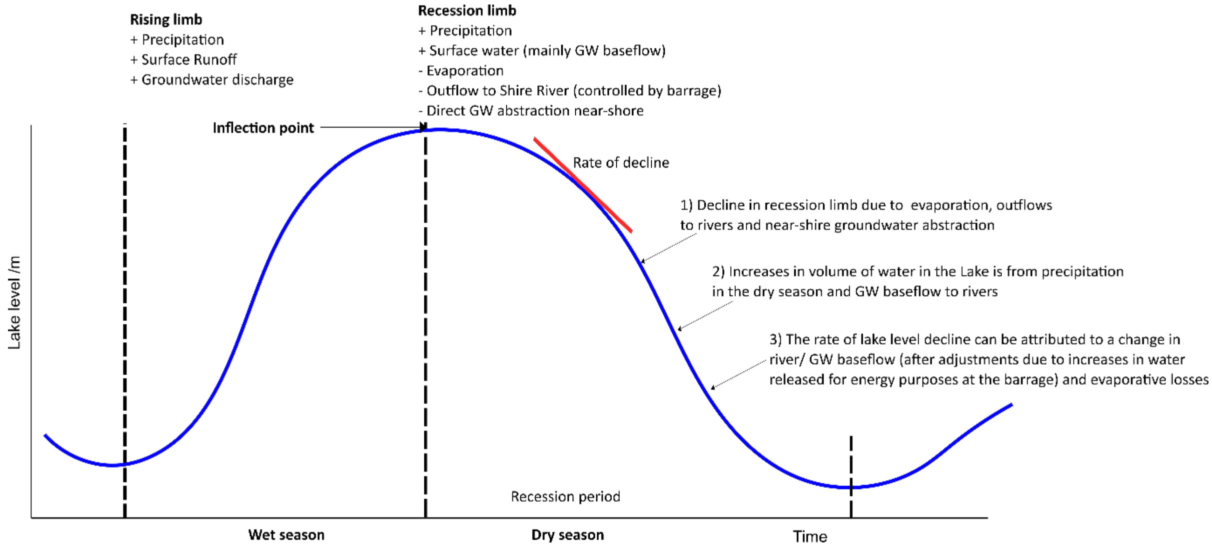


Figure 4: Defining the structure of Lake Malawi water level annual cycle. The rate of change is the differential of the lake level, an example rate of decline is shown here in red.

Further investigation of periodicity in Lake Level Change were analyzed using Discrete Fourier Transforms (Becker et al.,1988; Singleton 1979; Cooley et al., 1965) using the fft() function in the stats package, base R (R core team, 2024). The equation for a Discrete Fourier Transform is shown below as:

$$y[h] = \sum_{k=1}^{n} z[k]\ exp(-\frac{2\pi i(k-1)(h-1)}{n})$$

Equation 6: Discrete Fourier Transforms were used to identify dominant frequencies in precipitation (data from gauging stations from 1960), evapotranspiration, river/lake outflows, Lake Level and Lake Level Change/ slope. Where z is vector, h=1,..,n. l is the length of y.

2.4 Drivers of Lake Level change

To identify the most significant drivers of the change in Lake Level for given months, a multiple regression using a linear model for precipitation at different lag times was fitted to the change in Level Level (slope) using the lm() function in the stats package in base R. (Chambers et al., 1992; Wilkinson and Rogers, 1973). The variables were verified to ensure they met the assumptions of LM modelling of linearity, response distribution, independence of variables and multicollinearity. Assumptions of generalized linear modelling were checked for all LM models with all assumptions summarized in the appendix.

A linear model was developed for the average Lake Level change/ slope for the 3-month period leading up to a given month for 3, 6 and 12 month precipitation estimates leading up to the given month as well as the annual precipitation for individual years with lags of 1-15 years. For each LM, significant model variables (p value <0.1) were identified and a subsequent LM was generated based only on the significant variables. The multiple R-squared and adjusted R-squared for each model were also presented for the LM model generated for each month.

3. Results

The monthly and annual flow averages were calculated for each river station. These were summarised into total averages for each month and the total annual average. The annual average baseflow infex for rivers within each WRA are summarized in Table 3. All averaged monthly and annual values for total discharge, baseflow and surface flow for each station and individual hydrographs for each station are summarized in Appendix A. Overall, rivers in Malawi are effluent rivers, with the discharge increasing downstream. As the flows ranged from 1000's of m^3/s to less than 1 m^3/s, the values are rounded to two decimal places.

Table 3: Storage reserves estimates (Robin et al, 2013) with average annual BFI (Kelly et al, 2020)

WRA	**Storage Reserve (m^3)**		**Annual Average BFI***	**Rank**	
	Fractured rock aquifer	**Weathered rock aquifer**		**Storage**	**BFI**
1	$1.27x10^{7}$		0.64	5	5
2	$1.75x10^{6}$		0.32	14	14
3	$3.55x10^{6}$		0.57	8	7
4	$2.00x10^{6}$	$2.27x10^{7}$	0.49	4	9
5	$1.91x10^{6}$	$4.14x10^{7}$	0.68	1	4
6	$2.97x10^{6}$	$2.47x10^{7}$	0.37	3	12
7	$7.88x10^{6}$	$3.07x10^{7}$	0.73	2	3
8	$5.01x10^{6}$	$8.85x10^{5}$	0.60	7	6
9	$3.15x10^{6}$	$4.22x10^{6}$	0.51	6	8
10	$1.23x10^{6}$				
11	$1.99x10^{6}$		0.45	13	10
14	$3.18x10^{6}$		0.39	10	11
15	$2.77x10^{6}$		0.33	11	13
16	$3.47x10^{6}$		0.73	9	2
17	$2.73x10^{6}$		0.78	12	1

*calculated using Kelly et al (2020) average annual BFI values in Table 3.2

Hydrographs provided in the Appendix D show the baseflow and surface flow for individual WRAs over an average month. The highest flows occur during the wet season with the dry season experiencing the lowest flows. On some rivers, there is little to no flow during the dry season. The hydrographs show the flow from November to October to represent a hydrological year. WRA 1 has the highest total flows due to the River Shire being located within that area. Figure 4.2 shows the average flows for the northern, central and southern regions of Malawi plus the average river inflows into Lake Malawi. The northern region includes WRAs 7, 8, 9, 15, 16 and 17, central WRAs comprises of 3, 4, 5 and 6, and southern regions consisting of WRA 1, 2, 11 and 14. Overall, baseflow in the southern regions contributes to 88.10% of total discharge, however WRA's 2, 11 and 14 all have low BFI values (Table 3). This is due to the flows in WRA 1 being 3.75 to 120 times greater than rivers in the other areas therefore dominating the whole region.

The baseflow component of rivers discharge of rivers within the norther region, except in WRA 15, is very high. In central regions, there is a lower percentage of baseflow. In the south of Malawi, baseflow contributes to c. 90% of total river discharge. This shows that there is substantial groundwater storage throughout Malawi. The highest portion of baseflow is found in WRA 1 and the lowest portion of baseflow is in WRA 4, 6 and 14. By March, for most regions, and May for all WRAs, river discharge is dominated by groundwater flow with surface water making up a small percentage of the total flow. This coincides with Malawi's dry season.

A potential source of error is the varying quality in the data recorded for each river. Each gauge records a different length of time with up to 12% of the data missing (Kumambala, 2010). The number of months used to calculate the monthly average for each river gauge varied from month to month due to the data gaps. Potential reasons for the gaps are: errors with the method used to collect the data; equipment failure and issues with interpretation; mismanagement of data; and remoteness of river stations leading to the premature closure of the gauges (Kumambala, 2010).

As some rivers have multiple gauges present, the rivers selected to calculate the flow into Lake Malawi were: 3E1, 3E2, 3E3, 3F3, 4B1, 5C1, 5D3, 6D10, 7D8, 7G18, 8A5, 9A2, 9B7, 15A4, 15A8, 16E6, 16F2 and 17C6. These gauges are selected as they are the furthest downstream. There is a sampling error associated with volume of inflow into Lake Malawi as not all rivers flowing into the lake have gauging stations present on them. However, the volume of discharge from these rivers is predicted to be small. No suitable data is found from rivers flowing into the lake via Tanzania or Mozambique, including flows from the Ruhuhu and Kiwira, both of which are major tributaries of Lake Malawi.

Table 4 presents the volume of inflow from rivers into Lake Malawi alongside the baseflow and surface water components. The annual average inflow into the Lake from rivers is 357 m3/s, of which 65% originates from groundwater (Table 4). During the dry season, inflow from groundwater makes up c. 90% of the total inflow from rivers in Lake Malawi and decreases to c. 55% during the wet season (Table 4). This shows that groundwater flow dominates inflow into Lake Malawi all year round and is crucial to the health of surface waters.

Table 4: The volume of inflow from rivers into Lake Malawi split into baseflow and surface water components.

	Baseflow (m^3/s)	**Surface flow (m^3/s)**	**Total Discharge (m^3/s)**
November	55.71	34.68	99.40
December	157.26	126.09	283.35
January	315.99	257.38	573.37
February	449.01	363.04	812.05
March	478.38	365.50	843.87
April	384.95	262.46	647.42
May	269.51	33.52	303.03
June	174.52	19.94	194.46
July	139.25	15.53	154.46
August	113.97	12.35	126.32
September	88.81	9.47	98.29
October	69.54	7.29	76.83
Annual	229.04	128.01	357.06

3.2 Rainfall

The average national annual rainfall is estimated from daily rainfall data. A minority of stations recorded data from 1949 to 2016, with the majority starting to record in 1960, therefore there is a sampling error associated with the early data. To verify whether the annual average precipitation estimated from rainfall gauging stations accurately represented average precipitation across the entire LMSRB catchment, the average precipitation for the gauging stations was compared with average precipitation from remote sensing estimations for the basin from 1998-2011 using the Klinga-Gupta Efficiency (KGE). The KGE for the gauging station precipitation estimates and remote sensing precipitation was 0.519. The average precipitation estimates from the gauging stations were therefore deemed to provide a suitable approximation of average precipitation across the LMSRB.

3.2 Lake Level change

Figure 4 shows the change in lake level (with the trend in lake level shown) alongside solar irradiance and the southern oscillation index values. Visual inspection suggests some similar seasonality between irradiance and SOI, and Lake Level.

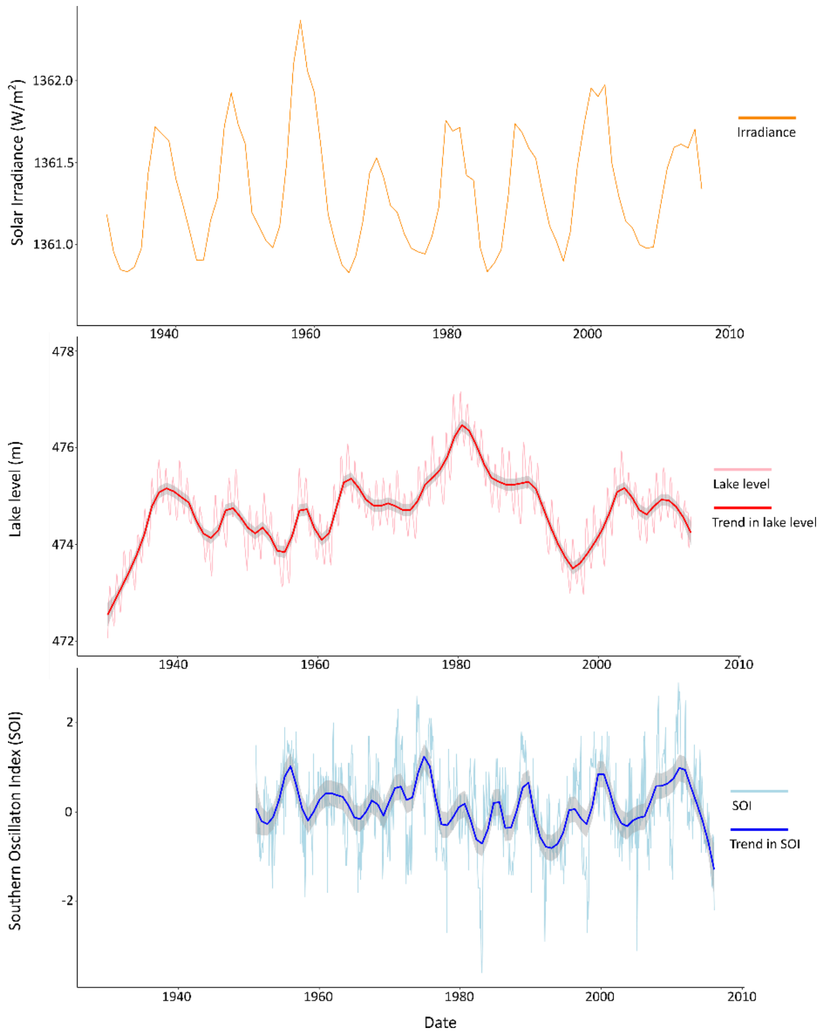


Figure 4: Solar irradiance (W/m^2), Lake Level (m), and Southern Oscillation Index (SOI).

Figure 5 shows the variation in Lake Level with local polynomial regression models (loess) at varying degrees of smoothing. The highest level of smoothing (fitting a smoothing parameter of 0.01) was selected as providing the best fit to Lake Level Change.

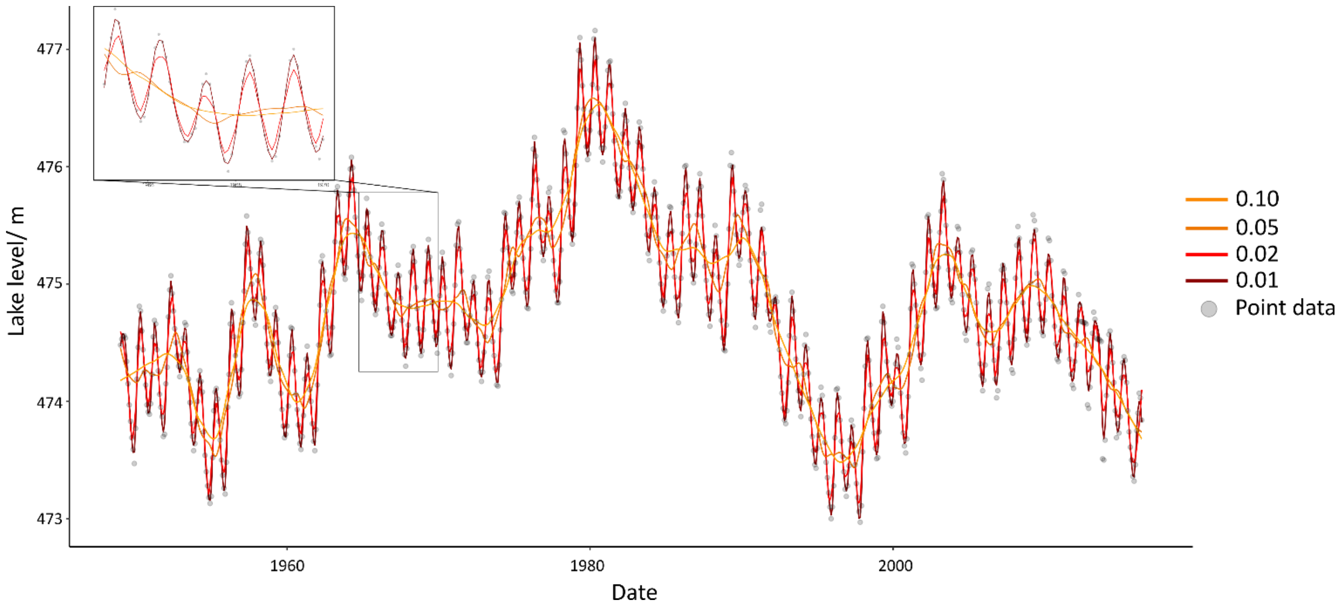


Figure 5: Lake level with polynomial regression models at different degrees of smoothing.

3.3 Rate of change of Lake Level

The rate of change of Lake Level is shown in Figure 6a with the annual moving average of lake level change also represented. The augmented Dickey-Fuller test was used to check for stationarity confirming that the rate of change of lake level met the stationarity assumption (p value 0.01).

Annual trends in the rate of change of lake level are shown in figure 6b with the rate of change of lake level calculated for each month shown. During the rainy season (November to April) there was a positive rate of change of lake level, indicating an increasing lake level. During the dry season (May to October), there was a negative rate of change in lake level. There was greatest variance in the rate of change of lake level during the rainy season with the dry season having less variation and the least variance in the rate of change of lake level in the month of August.

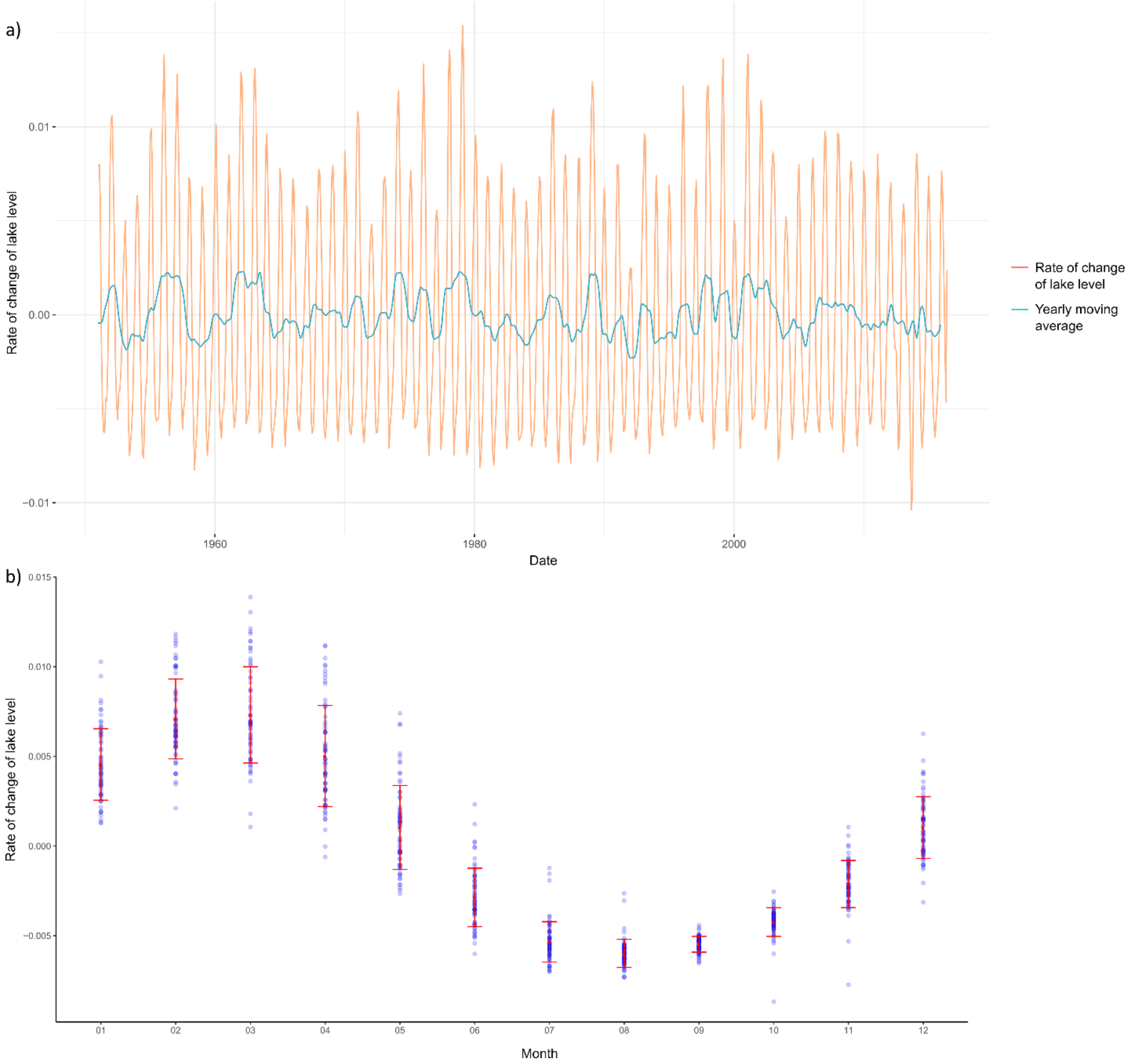


Figure 6: Rate of change of lake level. A) The rate of change of lake level with yearly moving average of the change in lake level. B) the average rate of change of lake level for a given month. There was little varitaiton in the rate of change in the dry season (May-October).

3.3 Periodicity of Lake Level Change

To further investigate the interannual variation in the rate of change of lake level seasonal decomposition was used on the moving annual average of lake level decline, figure 7. Seasonal decomposition by loess reveals periodic ‘seasonality’ of ~3-5 years.

We propose that the regular ‘seasonality’ observed is with underlying with underlying 10–20-year trends and patterns in lake level decline.

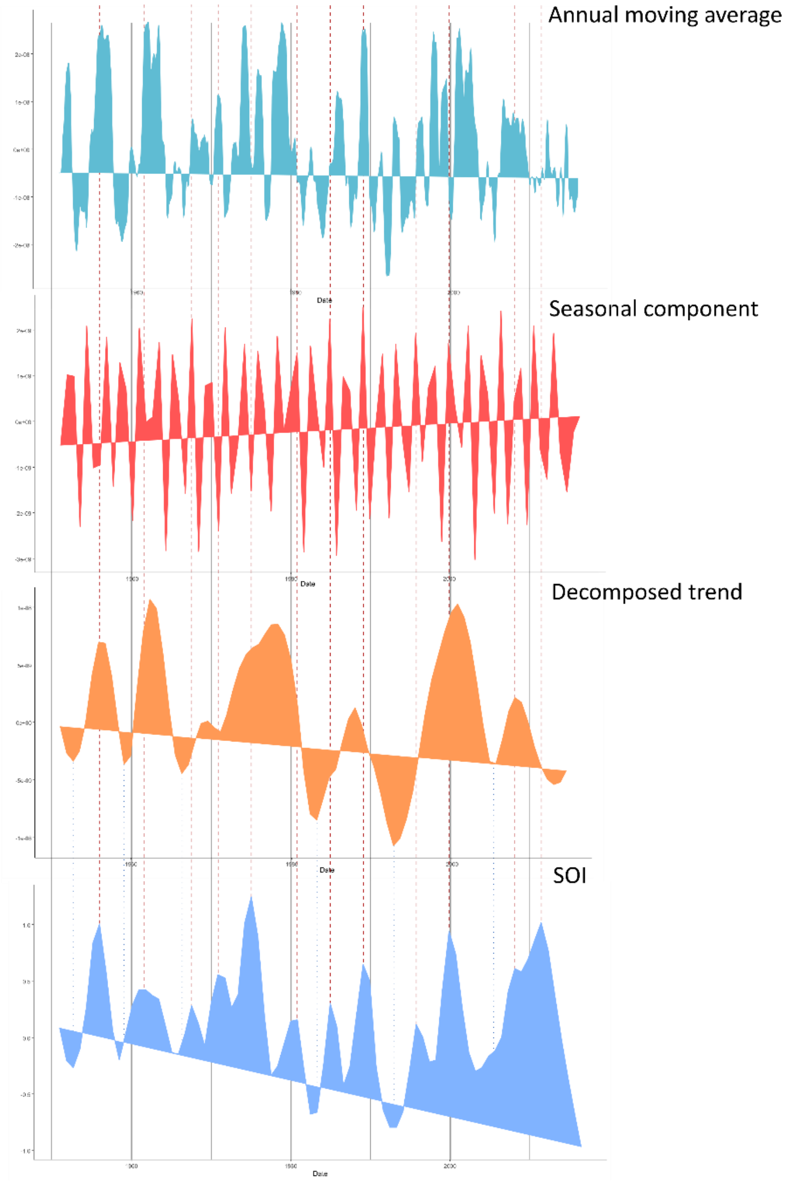


Figure 7: Seasonal decomposition of the rate of change of Lake Level plotted alongside SOI. There is an annual seasonal component as well as a decomposed trend, patterns in the decomposed trend and SOI, and how they connect with the annual moving average of the rate of change of Lake level, are emphasized by dashed lines.

Fourier transforms were used to extract significant frequencies in lake level dynaMICS. The periodicity of change in lake level is dominated by short periods which we suggest are largely influenced by lake/ river outflows regulated by the Kamuzu barrage. The rate of change is dominated by longer changes which we suggest align with longer patterns of change in precipitation and evapotranspiration. The results are shown in Table 5.

The observed 11 year cycle in lake level change/ slope, aligns with 11 year cycles in evapotranspiration and precipitation, coinciding with solar cycle. This is also the case for the 6 year periodicity observed in Lake Malawi storage. The 3 and 5 year changes in slope appear to be linked to periodic ENSO cycles (rounded to nearest month or year).

Table 5: Fourier transforms of patterns of precipitation, evapotranspiration, river/lake outflows, lake level, and rate of change of Lake level. Frequencies are ordered by signficance. Frequencies are rounded to the nearest month or year.

	Most significant frequency (to nearest month or year)				
	1st	2nd	3rd	4th	5th
Precipitation (gauging stations)	1 month	5 years	10 years	20 years	15 years
Evapotranspiration	1 month	6 years	16 years	11 years	5 years
River/ lake outflows	1 month	6 months	5 months	2 months	3 months
Lake level	1 month	2 months	3 months	4 months	6 months
Rate of change of Lake level	6 years	11 years	5 years	3 years	1 year

3.4 Drivers of Lake Level Change

Linear modelling was used to identify relationships between the rate of change of lake level and precipitation in the 3 months and year prior to the month investigated as well as average annual precipitation with of years up to 15 years prior, Table 6. There was high multicollinearity between precipitation 6 months prior to the month in question, as a result this was removed. All other assumptions, including multicollinearity, were met and are summarised in the Appendix E.

There is significant influence of precipitation in the 3 months prior to rate of change of lake level in the month of interest for 5 of the 12 months, months in which the 3 previous months of rainfall were within or around the rainy season were mostly influenced by precipitation in the 3 months. The rate of change lake level during May and June (end of the rainy season) was also significantly (positively) influenced by precipitation in the year preceding the measurement. The wet season rate of change of lake level was mostly not influenced by precipitation with a lag. There was a negative correlation between the rate of lake level change in March (middle of the wet season) and precipitation with a 14 year lag. In general the rate of lake level change during the rainy season was mostly influenced by precipitation in the same year and was not significantly influenced by previous years precipitation.

Conversely, the rate of change of lake level during the dry season (August to October) was not influenced by precipitation in the year of interest (for 3 months or 12 months). However, the rate of lake level decline was strongly (negatively) influenced by precipitation in preceding years with precipitation in 1, 4,5, 7, 10,12 and 14 years prior to the analysed Lake Level all significant to the rate of change of Lake Level. All preceding years precipitation events had a negative correlation with Lake Level change; when there was high rainfall in previous years leading up to the year of interest, the rate of decline of Lake Malawi's storage was reduced.

Table 6: Influence of precipitation level in 3 and 12 months prior to month of interest of lake level change and average annual precipitation in years prior to month of interest with lag of 1-15 years.

Rain pattern in 3 months prior	Month of lake level change	Precipitation month prior		12-month precipitation with lag year														
		3	12	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Transition	Jan	+										+	-		+			
Rainy	Feb																	
Rainy	Mar	+															-	
Rainy	Apr																	
Rainy	May	+	+															
Transition	Jun	+	+													+		
Transition	Jul			-	-													
Dry	Aug			-						-								
Dry	Sep						-	-					-				-	
Dry	Oct														-		-	
Transition	Nov	+															-	
Transition	Dec																	

Analysis of stable isotopes was also conducted to explore the drivers of change in Lake Malawi storage. Lake Malawi water samples had higher percentage make up of $\sigma^{18}O$ and $\sigma^{2}H$ showing more similar isotope signatures to groundwater than precipitation and suggesting that storage in Lake Malawi is dominated by groundwater derived sources of water.

[To be completed after publication of Banda et al 2024 paper in Revision]

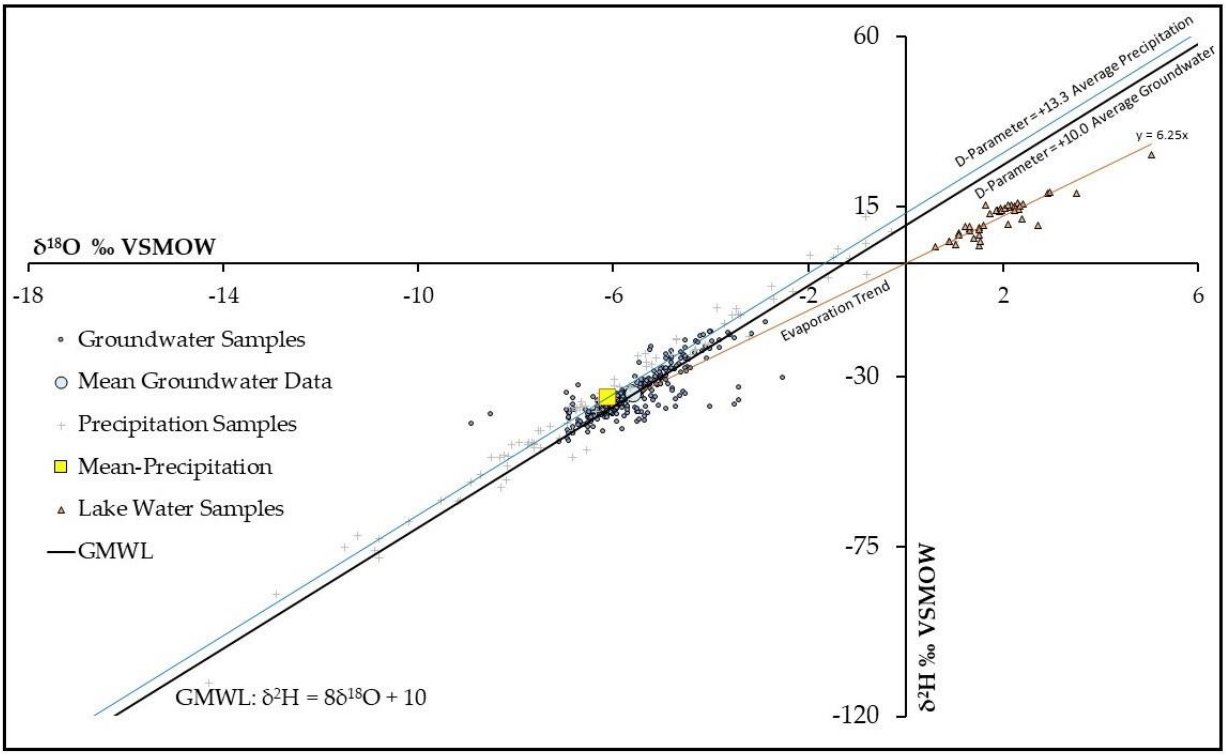


Figure 9. Stable Isotopes of Precipitation, Groundwater and Lake Malawi Water [After Banda et al 2024]

5. Discussion

5.1 River Flow and Baseflow

Analysis of monthly average flows and annual flows shows that groundwater contributes substantial volumes to total river discharge. BFI trends vary for different river systems within Malawi. In WRA 1, the river stations on the Shire, all have BFI’s of 0.9 or greater, suggesting that the groundwater storage in the aquifers that it flows over is very high. The Linthipe’s BFI decreases at station 4C11, where the river goes from flowing over weathered basement aquifers to fractured basement aquifers. However, it increases further downstream. This suggests that the weathered basement aquifers have slightly higher storage than the fractured. As these aquifers are relatively small and discontinuous, the river likely flows over multiple aquifers. The rivers in WRA 5, 6, 7, 9 and 14 also flow over fractured aquifers but the BFI varies from 0.28 to 0.87 indicating there is a heterogeneous nature within the fractured aquifers. Change in BFI will also be due to different land uses and abstraction rates of groundwater in different WRAs. An increase in BFI downstream indicates that there is a decrease in the volume of groundwater abstracted while a decreasing trend is indicative of higher groundwater abstraction rates. BFI values for rivers such as the Songwe and rivers within WRA 14 will also depend on groundwater uses within Tanzania.

The hydrographs for WRAs 2, 4, 6, 11, 14 and 15 show that baseflow in these regions is less substantial than elsewhere in Malawi (Appendix D). This suggests that the groundwater storage is lower in these regions compared to elsewhere in Malawi. Kelly et al (2020) estimates that the annual average BFI for these regions are: 0.46, 0.49, 0.37, 0.45, 0.39 and 0.33 respectively. The aquifer types do not significantly change between these WRA's and other regions in Malawi. Robins et al (2013), calculated the available groundwater resource and the volume abstracted and found that in WRA's 4, 5, 11 and 14 there was an overall negatively balance in the fractured (WRA 4, 5, 11 and 14) and weathered (WRA 4 and 5) basement aquifers, suggesting that the abstraction rate in these regions is unstainable and is the cause of the lower baseflow in these areas. However, Kelly et al (2020) calculated the average annual BFI for WRA 5 to be 0.68. In WRA 4 and 5 there is both fractured and weathered basement aquifers present yet the fractured aquifers within WRA 5 have a greater positive balance compared to the fractured aquifers in WRA 4 (Robins et al, 2013; NHA, 2018). The fractured in the aquifers in WRA 5 may also have a higher connectivity resulting in a higher permeability and a higher BFI. WRA's 2, 6 and 15 are calculated to have a small positive balance

(Robins et al, 2013) suggesting that there is another factor contributing to the low baseflow and groundwater storage. A potential reason for the low BFI in WRA 2 is the presence of Lake Chilwa where rivers drain into. Aquifers in WRA 15 may interact differently with Lake Malawi compared to other WRA's along the lake, resulting in a lower storage and baseflow. Geological heterogeneity is also likely to be the reason for the lower BFI in all six regions with the strata having a lower permeability. Land use will also influence the groundwater storage in Malawi. WRA's 2, 4, 6, 11 and 14 are situated along Malawi's border and while the rivers in WRA 2 drain to Lake Chilwa and the rivers in 4 and 6 drain to Lake Malawi, groundwater catchments do not mirror river catchments, therefore the baseflow in these areas will be affected by groundwater abstraction in Zambia and Mozambique.

Using the specific yield of aquifers within each WRA, Robin et al (2013) approximates the storage reserve of weathered and fractured aquifers in Malawi. As there are no river stations located in WRA 10, the BFI cannot be compared to the storage reserve. There is a sampling error associated with comparing the BFI data to the storage volumes as in some WRAs there are very few stations. It should be noted that the storage reserves do not account for alluvium, or consolidated sediment aquifers which are widespread in the southern WRAs. These two factors may account for the discrepancies between the ranks of each data set (Table 3). Overall, the storage estimates correlate to the average annual BFI (except for WRA 4, 9, 16 and 17), Table 3, showing that BFI can be used to estimate the groundwater storage. There does not appear to be a spatial trend of high groundwater storage, with high reserves located in the north, centre, and south of Malawi.

Overall, the southern region on Malawi has the highest volume of recharge within Malawi (NHA, 2018) contributing to the high baseflow (88.10%) and groundwater storage in the region. Geologically and hydrogeologically, the WRA's within the northern and central region are similar (Fraser et al, 2020). Yet, along the northern border with Tanzania and Zambia, there is a recharge rate of c. 3 mm/day (NHA, 2018) which is likely to be why there is a higher percentage of baseflow in the northern region (69.79%) compared to the central region (56.69%). There is also a greater number of weathered basement aquifers within the central region of Malawi, potentially contributing to the lower portion of baseflow.

Table 4 shows the average volumes of river inflow into Lake Malawi with the surface and baseflow component. Groundwater flow dominates the inflow all year round, increasing during the dry season when precipitation is not filling the rivers, and rivers are more dependent on baseflow. Therefore, to maintain the current lake level, groundwater abstraction rates will need to be monitored and controlled all year round.

5.2 Seasonality of Lake Level Change

Visually inspecting changes in Lake Malawi storage suggested some influence of established weather patterns of solar irradiance and SOI. As Lake Malawi is controlled by a number of factors, notably the presence of the Kamuzu Barrage (Bhave et al., 2022), the rate of change of lake level was used to explore seasonality.

Decomposition analysis was used to explore trends in annual trends of the rate of change of lake level. Decomposition revealed a strong seasonal trend with annual variation of the rate of change of lake level, this is as expected with a positive rate of change of lake level during the wet reason and a negative rate of change during the dry season. In addition to annual patterns, there was a decomposed trend observed which exhibited approximately 10–20-year cycles in lake level change alongside 3-5 year patterns. The decomposed trend of lake Malawi storage aligned with the SOI trend in Malawi.

Further analysis of patterns in lake level change was conducted through Fourier transform to identify the underlying frequencies in the rate of change of lake level. Fourier transform revealed 11-year cycles in evapotranspiration and precipitation, coinciding with solar cycle. There were also 3- and 5-year changes observed within the decomposed trend, these aligned with periodic ENSO cycles and were also observed within the Fourier transform of precipitation patterns.

These results suggested that Lake Malawi's storage experienced seasonality which was influenced by patterns in solar intensity and meteorological events.

5.3 Rate of Lake Level Change

To further investigate the drivers of Lake Malawi's storage change, a linear regression model was produced for the rate of change of Lake Malawi level for each month. The rate of change of storage for a given month was compared to precipitation levels in the 3 months and 12 months preceding the month to evaluate the influence of the precipitation of that year as well as average precipitation in the years preceding the year of interest (with lags of 1-15 years).

The rate of change of Lake level during the wet season was significantly influenced by precipitation events in that year, in the 3 months and 12 months prior to the month of interest. Conversely, during the dry season, the rate of change of Lake level was not significantly influenced by precipitation in year in question but was significantly influenced by the level of precipitation in preceding years with lags of 1, 4, 5, 7, 10, 12, and 14 years. In all cases, there was a negative correlation between previous precipitation and the rate of lake level decline; when previous years experienced intense rainfall, Lake Level declined at a slower rate. These findings suggest that the rate of change of Lake level during the dry season is more influenced by previous precipitation events than by precipitation in the same year. This points to a system providing a buffer of previous high precipitation events limiting the rate of Lake Level decline. As groundwater recharges strongly during high precipitation years (Kalin et al., 2022), we propose that the influence of previous precipitation events on Lake Malawi level is mediated through baseflow from groundwater storage.

5.4 Stable Isotopes of Groundwater and Lake Malawi Water.

[Section to be completed on publication of Banda Lake Malawi Basin Paper, in Revision for imminent publication 26th April 2024].

5. Conclusions

To conclude, as Malawi's population increases and climate change puts additional stress on surface water resources, groundwater is becoming increasingly important within Malawi. Currently, it is one of the main sources of clean water. However, it is still susceptible to contamination and over abstraction. In order for Malawi to achieve SDG6, sustainable management of groundwater is required.

Malawi's topography, geology, and hydrogeology are all strongly influenced by the EARS. The topography consist of upland plateaus in the Northern and central regions and the South is dominated by the Lower Shire Valley. Metamorphic rocks, mostly gneisses, make up the majority of Malawi's geology in the form of the basement complex. As the rocks are somewhat resistant to weathering, they make up all the geology in Malawi's highlands. Due to extension events associated with the EARS, the unit has experienced both chemical and physical deformation. Therefore, the unit is split into two aquifer types: weathered basement aquifers and fractured basement aquifers. These are relatively small and unconnected. Quaternary alluvium deposits are extensive to the South of Malawi and form alluvium aquifers.

All rivers that originate in the Northern and central regions of Malawi drain into Lake Malawi. Rivers in the south drain into multiple systems, with the Shire River being the main one. Daily river data has been collected for many decades yet there is a significant percentage of missing data for all rivers within Malawi. The period of recorded at gauging station also varies. Therefore, the monthly average flows are calculated for all rivers. This also allowed for the estimation of river recharge to Lake Malawi to be carried out. Rainfall data has also been recorded for several decades in Malawi, yet the period recorded by stations differs. Hence, the average annual rainfall is approximated for 1949 to 2016.

Previous studies calculate a water balance model for Lake Malawi, these however do not consider groundwater. This adds a large degree of uncertainty to the findings of these studies as baseflow contributes a larger volume of water to river flow in Malawi than surface runoff. Robins et al (2013) estimate the groundwater storage within Malawi and find that in several WRAs there is a greater volume of water being abstracted from aquifers than is being replenished. However, the study does not mention how this impacts the health of surface waters in Malawi.

The main findings of this study are as follows. Baseflow makes up a higher portion of river discharged that surface runoff for most of the rivers located in Malawi, with nearly all of river flow during the dry season deriving from baseflow. This indicates that there is a considerable volume of groundwater storage throughout the country with the greatest storage capacity located in alluvium aquifers. On average, the proportion of baseflow decreases from the Northern to the central region of Malawi, however it is at its highest in Southern Malawi where the alluvium aquifers are.

As Malawi is a landlocked country, river flow and precipitation are the only inflows to Lake Malawi. Groundwater storage therefore significantly impacts the water level of Lake Malawi. Annually, the inflow from groundwater is 7.22×10^9 m^3/year, 65% of total discharge.

The rate of change of Lake Malawi's level is investigated through decomposition analysis, Fourier transform, and linear modelling. Two cycles impact Malawi's rainfall: the ENSO and sunspot cycle. Periodicity in evapotranspiration and rainfall, aligning with these cycles, is observed. In addition, the rate of change of Lake Malawi's storage is also influenced by these cycles.

Groundwater monitoring is still relatively new in Malawi , with the earliest being from 2009, therefore there is not a long enough record to accurately compare groundwater storage to the rate of lake level decline. Rainfall is the main source of aquifer recharge, thus this is used to see if there is a relationship between the two. The rate of lake level change is estimated for each month and compared to precipitation for the given year and previous years (with lags of 1-15 years) through a linear model to identify significant correlations. During the wet season, when Lake Malawi levels are increasing, the rate of change of lake level is significantly positively influenced by precipitation in that given year. This suggests that, during the wet season, change in Lake Malawi level is influenced by direct precipitation at the lake and discharge from surface flow. The rate of change of lake level during the dry season is not influenced by precipitation in the preceding months and year but is influenced by precipitation intensity with lags of 1-14 years. We conclude that the influence of the rate of change of Lake Level from previous precipitation events is mediated by groundwater influencing baseflow and Malawi Lake Level.

5.2 Recommendations

No suitable river or baseflow data from Tanzania and Mozambique are available in order to assess what the total inflow into Lake Malawi is. In addition, not every river within Malawi has a river station located on it. Therefore, it is suggested that rivers without a river gauge are monitored to obtain a more accurate value of the inflows into Lake Malawi. Rivers flowing into the lake from Tanzania and Mozambique should also be monitored to obtain a more comprehensive view of the total inflow from river discharge to Lake Malawi.

Fraser et al (2020) suggests that there are aquifers beneath Lake Malawi which may be an additional source of water for the lake, or indeed that the lake may be losing water to them. Geological and hydrogeological maps from Malawi, Tanzania, and Mozambique should be analysed to see if there are any aquifer bearing units beneath the lake. Isotopic studies should also be carried out to confirm the presence of these aquifers and what relationship they have with Lake Malawi.

As groundwater storage is shown to be the main source of recharge for the lake, next to precipitation, groundwater abstraction and baseflow levels should be analysed in Tanzania and Mozambique to see how the discharge is affected. Fraser et al (2020) found c. 40 transboundary aquifers with Mozambique, Tanzania, and Zambia. The rivers that flow into Lake Malawi flow over several of these aquifers, therefore the abstraction rate should also be monitored in all neighbouring countries. A transboundary diagnostic analysis (TDA) should be carried out on all of the aquifers so that a sustainable management plan can be derived and the baseflow component of Malawi’s rivers is not diminished.

Lake Malawi is a transboundary resource and a critical economic, ecological, and environmental factor for all the nations that share it. Despite this, no agreement on how this sharing takes place, or indeed a sustainable management plan, is ineffect. In order for the resource to be available to all three countries in the future, a TDA should be undertaken for the lake. This will also allow for the three countries to work towards SDG 6.

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Appendix A: Total monthly average discharge (m^3/s) for each station

Table 1: Monthly average discharge m^3/s

Gauge ID	November	December	January	February	March	April	May	June	July	August	September	October	Annual
1B1	261.97	268.69	307.33	347.75	374.64	404.19	412.74	387.69	357.02	315.75	287.25	271.16	334.36
1C1	2.35	4.43	8.15	10.97	6.65	3.65	3.59	2.59	2.47	2.14	1.88	1.77	4.23
1G1	534.46	699.86	910.64	1083.52	1140.56	1032.53	962.08	906.25	822.37	723.98	621.40	579.64	827.88
1K1	4.60	3.99	16.80	26.72	24.57	5.43	2.05	1.07	0.70	0.65	0.28	0.05	10.09
1L12	495.13	531.44	615.81	682.44	706.91	674.88	667.71	639.62	568.04	561.86	528.83	514.05	595.07
1M1	3.19	7.62	9.91	8.98	10.65	6.47	4.54	3.68	3.09	2.60	1.99	2.14	5.40
1P2	231.67	253.26	313.26	377.54	391.79	421.57	431.19	392.20	350.88	313.88	276.89	237.29	328.35
1R3	2.91	14.79	30.76	44.80	38.04	12.54	3.87	2.10	1.84	1.40	1.07	0.94	11.94
1S7	0.25	1.37	2.80	7.39	5.79	1.40	0.49	0.31	0.22	0.16	0.13	0.04	1.53
2B22	1.19	4.69	6.16	9.34	5.66	2.32	1.25	1.01	0.87	0.72	0.73	0.71	2.87
2B33	1.72	10.80	10.40	17.34	9.60	2.01	0.82	0.55	0.41	0.34	0.32	0.26	3.93
2C3	0.39	1.33	3.00	3.29	3.20	2.65	1.52	0.86	0.55	0.37	0.24	0.17	1.45
3E1	0.66	1.65	2.65	2.51	2.50	1.53	1.01	0.78	0.25	0.59	0.59	0.57	1.35
3E2	0.26	2.02	3.64	6.40	4.11	2.55	1.32	0.70	0.57	0.38	0.27	0.34	1.62
3E3	0.73	5.06	9.84	17.29	11.08	4.00	1.86	1.23	1.01	0.79	0.64	0.52	4.42
3E5	0.27	1.24	3.21	2.81	2.32	1.37	0.93	0.66	0.54	0.44	0.33	0.24	1.20
3F3	1.20	3.57	6.44	8.16	7.54	4.47	2.41	1.73	1.44	1.20	1.25	0.66	3.07
4B1	5.83	52.27	132.33	196.51	162.32	76.47	29.95	10.64	8.24	5.92	3.89	2.23	57.02
4B3	0.39	11.03	11.98	22.87	14.39	4.42	1.29	0.56	0.35	0.21	0.10	0.06	5.27
4B4	1.20	7.85	21.56	32.12	26.82	12.48	4.19	2.12	1.52	0.98	0.45	0.32	9.42

4B9	1.78	32.43	59.89	79.41	88.42	37.68	7.98	4.13	3.18	2.29	1.35	0.99	26.29
4C2	4.46	24.32	56.99	69.72	54.56	25.88	9.99	6.70	5.40	4.30	2.92	2.06	23.44
4C11	2.25	8.72	34.91	40.23	43.72	5.13	1.38	1.05	0.56	0.32	0.17	0.09	13.18
4D4	0.91	4.06	10.99	18.45	16.46	8.01	4.07	2.22	1.61	1.12	0.72	0.55	6.76
4D24	1.10	3.97	9.20	11.66	11.06	8.44	3.10	1.79	1.20	0.89	0.73	0.90	4.31
4E2	0.83	3.56	8.14	11.03	7.93	2.33	0.74	0.41	0.40	0.35	0.23	0.15	3.16
5C1	13.71	41.14	82.38	135.23	149.99	101.65	54.58	37.93	31.81	28.43	22.24	16.26	61.62
Gauge ID	**November**	**December**	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**Annual**
5D1	5.56	21.51	70.69	113.20	103.36	48.29	13.14	3.43	1.88	1.15	0.62	1.66	31.81
5D2	0.11	5.92	37.22	112.97	149.37	78.64	19.00	5.58	2.95	1.43	0.48	0.18	43.88
5D3	0.48	1.66	2.85	3.81	3.55	1.99	1.51	1.32	1.27	1.12	0.80	0.54	1.63
5E6	0.25	0.59	1.62	1.78	2.05	0.98	0.56	0.44	0.33	0.27	0.19	0.16	1.02
5F1	0.03	0.88	10.08	24.30	28.11	14.40	5.29	1.21	0.67	0.39	0.21	0.07	7.70
6C1	0.03	2.46	12.64	34.58	37.93	9.04	0.98	0.26	0.14	0.08	0.02	0.01	11.80
6C5	0.14	0.76	2.31	3.49	5.34	1.34	0.50	0.29	0.14	0.07	0.06	0.01	1.48
6D10	1.45	21.57	49.27	62.14	69.27	38.74	11.41	5.98	3.86	2.72	1.31	0.64	23.78
7A3	0.58	6.28	39.82	65.71	57.16	20.00	3.76	1.79	1.15	0.67	0.33	0.14	15.72
7D8	1.31	3.19	7.33	6.47	6.84	6.89	3.66	2.64	2.05	1.41	0.94	0.70	3.43
7E2	2.73	19.04	120.29	203.17	179.80	59.75	28.61	11.89	8.94	4.90	2.01	0.57	48.81
7F1	2.20	4.24	8.61	14.77	20.28	12.99	7.75	5.55	4.37	3.53	2.70	2.18	7.35
7F2	2.33	4.50	7.98	9.13	11.55	12.25	8.59	6.24	5.14	3.98	3.04	2.38	6.83
7G14	5.19	14.32	47.18	72.19	80.99	59.03	25.63	15.82	12.29	9.60	7.16	5.05	29.86
7G18	7.87	23.48	78.43	117.54	115.19	88.87	32.85	22.08	16.42	12.88	8.91	6.41	43.44
7H1	3.82	5.99	8.59	9.94	12.98	13.75	9.62	7.30	6.01	5.06	4.20	3.56	7.61
7H2	1.64	2.25	2.73	3.07	4.08	5.19	3.74	2.88	2.53	2.18	1.91	1.71	2.80

7H3	8.00	18.33	29.92	37.43	43.41	55.17	30.84	17.93	14.62	12.43	6.50	7.45	26.85
8A5	8.41	17.24	24.68	35.61	52.30	26.43	12.12	8.08	7.95	7.94	7.44	7.76	18.87
9A2	4.06	13.20	24.82	27.70	38.69	28.93	11.48	7.17	5.42	4.12	3.25	2.47	14.28
9A4	0.81	3.63	7.39	12.82	8.84	5.06	2.43	1.89	1.51	1.16	0.82	0.64	4.66
9A5	0.50	1.08	1.46	1.74	2.45	2.10	1.35	0.97	0.79	0.60	0.46	0.35	1.15
9B3	2.98	1.44	6.62	7.78	6.99	3.48	1.03	0.73	0.40	0.25	0.55	3.86	5.03
9B5	0.10	0.74	2.51	5.18	2.69	0.92	0.27	0.12	0.09	0.07	0.05	0.03	1.90
9B6	1.12	5.70	13.64	25.63	23.12	10.58	2.53	1.49	1.13	0.80	0.53	0.49	7.26
9B7	16.91	48.16	71.57	100.58	110.38	142.41	57.82	34.86	24.91	19.68	17.15	13.29	57.20
11A6	0.25	1.70	2.58	3.09	4.13	1.14	1.14	0.35	0.27	0.22	0.18	0.12	1.12
11A7	0.09	0.80	0.73	0.39	0.48	0.18	0.10	0.07	0.05	0.05	0.04	0.03	0.46
14A2	9.56	19.48	29.61	22.05	13.84	7.13	4.71	4.40	4.13	3.78	3.08	2.50	15.69
14A3	0.71	2.43	4.42	4.05	2.17	0.66	0.32	0.18	0.14	0.10	0.07	0.08	1.43
Gauge ID	**November**	**December**	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**Annual**
14B2	3.47	18.27	36.08	53.16	40.00	12.42	4.46	2.98	2.40	1.86	2.15	1.51	16.03
14C2	8.80	9.84	10.83	10.94	13.51	13.33	11.86	12.26	13.27	10.72	9.57	8.52	10.89
14C8	3.72	9.38	13.75	15.88	19.46	14.07	5.85	4.10	4.07	2.90	1.98	2.38	8.09
14D1	90.34	103.58	169.04	349.15	318.52	168.15	88.47	66.78	57.64	52.14	37.76	35.44	154.49
15A4	0.23	5.29	6.70	7.43	7.12	2.35	0.88	0.75	0.39	0.28	0.21	0.18	2.85
15A8	0.96	4.34	13.93	23.07	14.48	6.37	2.49	1.49	1.26	0.98	0.79	0.61	5.05
16E6	10.98	15.25	18.51	19.38	21.92	28.87	20.07	18.50	17.55	15.78	12.63	11.35	19.83
16F1	2.09	2.79	3.20	3.98	5.96	7.90	5.54	3.52	2.67	2.13	1.49	1.42	3.52
16F2	14.47	22.25	34.26	38.24	60.33	78.15	53.60	35.80	28.49	20.59	14.84	11.51	34.68
17C6	0.90	2.01	3.72	3.97	6.27	6.75	3.98	2.78	1.89	1.51	1.11	0.79	2.90
17C10	0.40	0.61	0.97	1.40	2.63	3.15	1.69	0.99	0.76	0.62	0.53	0.47	1.16

Appendix B: Total monthly average baseflow (m^3/s) for each station

Table 2: Average monthly baseflow m^3/s

Gauge ID	November	December	January	February	March	April	May	June	July	August	September	October	Annual
1B1	248.87	255.26	291.97	330.36	355.90	383.98	404.48	379.94	309.44	281.51	265.74	265.74	324.33
1C1	1.03	1.95	3.59	4.83	2.92	1.61	3.05	2.20	2.10	1.82	1.60	1.50	2.03
1G1	497.04	650.87	846.90	1007.67	1060.72	960	942.84	888.12	805.92	709.50	608.98	568.05	786.49
1K1	1.52	1.32	5.54	8.82	8.11	1.79	1.56	0.81	0.53	0.49	0.21	0.04	3.84
1L12	450.57	483.61	560.39	621.02	643.29	614.14	641.00	614.04	545.32	539.39	507.68	493.49	547.46
1M1	1.66	3.96	5.15	4.67	5.54	3.37	3.95	3.20	2.69	2.26	1.73	1.86	3.45
1P2	201.55	220.33	272.54	328.46	340.86	366.77	401.01	364.75	326.31	291.91	257.51	220.69	295.51
1R3	0.47	2.40	4.92	7.17	6.09	2.01	3.37	1.82	1.60	1.22	0.93	0.82	2.27
1S7	0.07	0.38	0.78	2.07	1.62	0.39	0.37	0.24	0.17	0.13	0.10	0.03	0.49
2B22	0.37	1.46	1.91	2.90	1.75	0.72	0.98	0.80	0.69	0.56	0.57	0.56	1.03

2B33	0.38	2.40	2.29	3.82	2.11	0.44	0.65	0.43	0.32	0.27	0.25	0.20	1.06
2C3	0.28	0.96	2.16	2.37	2.30	1.91	1.41	0.80	0.51	0.34	0.23	0.16	1.10
3E1	0.28	0.69	1.11	1.06	1.07	0.65	0.94	0.73	0.24	0.56	0.56	0.53	0.66
3E2	0.15	1.17	2.11	3.71	2.38	1.48	1.14	0.60	0.49	0.33	0.23	0.29	0.90
3E3	0.31	2.18	4.23	7.44	4.76	1.72	1.68	1.11	0.91	0.71	0.58	0.47	2.39
3E5	0.13	0.62	1.60	1.41	1.16	0.68	0.88	0.62	0.52	0.41	0.33	0.22	0.66
3F3	0.77	2.28	4.12	5.22	4.83	2.86	2.24	1.61	1.34	1.12	1.17	0.61	2.21
4B1	2.27	20.39	51.61	76.64	63.30	29.82	23.36	8.30	6.43	4.62	3.04	1.74	24.52
4B3	0.19	5.29	5.75	10.98	6.91	2.12	1.15	0.50	0.32	0.18	0.09	0.05	2.74
4B4	0.70	4.57	12.50	18.63	15.56	7.24	3.69	1.87	1.34	0.86	0.39	0.28	5.98
4B9	0.38	11.67	21.56	28.59	31.83	13.57	6.14	3.18	2.45	1.76	1.04	0.76	9.73
4C2	1.93	10.19	23.94	29.28	22.91	10.87	9.09	6.10	4.92	3.91	2.66	1.87	11.95
4C11	0.38	1.68	5.93	6.84	7.43	0.87	1.03	0.79	0.42	0.24	0.13	0.07	2.77
4D4	0.53	2.39	6.49	10.88	9.71	4.72	3.74	2.04	1.46	1.03	0.66	0.51	4.39
4D24	0.74	2.66	6.17	7.81	7.41	5.66	2.70	1.55	1.04	0.77	0.64	0.78	3.01
4E2	0.35	1.28	3.01	4.08	2.94	0.86	0.59	0.33	0.32	0.29	0.17	0.10	1.17
5C1	9.46	28.39	56.84	93.31	103.49	70.14	51.31	35.65	29.90	26.72	20.90	15.29	45.60
Gauge ID	**November**	**December**	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**Annual**
5D1	3.98	15.60	52.31	83.77	76.49	35.73	12.22	3.19	1.74	1.07	0.57	1.54	23.86
5D2	0.08	4.38	27.54	83.59	110.54	58.19	15.96	4.69	2.48	1.20	0.41	0.15	33.35
5D3	0.21	0.75	1.28	1.71	1.60	0.90	1.27	1.11	1.07	0.94	0.68	0.46	0.78
5E6	0.12	0.27	0.75	0.82	0.94	0.45	0.51	0.39	0.30	0.25	0.17	0.14	0.55
5F1	0.03	0.70	7.96	19.20	22.21	11.38	4.71	1.08	0.60	0.34	0.19	0.06	6.16
6C1	0.01	0.69	3.54	9.68	10.62	2.53	0.81	0.22	0.12	0.06	0.01	0.00	3.30
6C5	0.06	0.33	0.99	1.50	2.30	0.58	0.37	0.21	0.10	0.06	0.05	0.01	0.69

6D10	0.55	8.20	18.72	23.61	26.32	14.72	8.10	4.24	2.74	1.93	0.93	0.45	8.32
7A3	0.20	2.21	13.96	22.96	20.01	6.99	2.75	1.30	0.84	0.49	0.24	0.11	5.50
7D8	0.54	1.31	3.01	2.65	2.80	2.82	3.08	2.22	1.72	1.19	0.79	0.59	1.82
7E2	1.94	6.99	85.41	144.25	127.66	42.42	24.89	10.34	7.78	4.27	1.75	0.49	34.65
7F1	1.59	3.05	6.20	10.63	14.60	9.35	7.44	5.33	4.20	3.39	2.60	2.09	5.88
7F2	1.79	3.46	6.15	7.03	8.89	9.43	8.33	6.05	4.98	3.86	2.94	2.31	5.80
7G14	3.90	10.90	35.86	54.92	61.59	44.94	24.87	15.34	11.93	9.32	6.94	4.88	23.89
7G18	5.90	17.61	58.82	88.16	86.39	66.65	31.87	21.42	15.93	12.49	8.64	6.22	36.49
7H1	2.98	4.68	6.70	7.76	10.12	10.72	9.43	7.15	5.89	4.96	4.12	3.49	6.39
7H2	1.29	1.78	2.15	2.43	3.22	4.10	3.58	2.76	2.43	2.09	1.83	1.64	2.43
7H3	4.80	11.00	17.95	22.46	26.05	33.10	28.68	16.68	13.60	11.56	6.04	6.93	19.07
8A5	4.62	9.48	13.57	19.59	28.76	14.53	11.03	7.36	7.24	7.23	6.77	7.06	11.32
9A2	2.24	7.26	13.65	15.23	21.28	15.98	10.56	6.60	4.98	3.79	2.99	2.27	10.14
9A4	0.49	2.06	3.92	6.79	4.68	2.68	2.23	1.73	1.39	1.06	0.76	0.59	3.42
9A5	0.26	0.57	0.77	0.92	1.30	1.12	1.24	0.89	0.73	0.55	0.42	0.32	0.72
9B3	0.95	0.46	2.12	2.49	2.24	1.11	0.80	0.57	0.31	0.20	0.43	3.01	1.66
9B5	0.02	0.15	0.53	1.09	0.56	0.19	0.19	0.08	0.06	0.05	0.03	0.02	0.48
9B6	0.49	2.51	6.00	11.28	10.17	4.65	2.38	1.40	1.06	0.75	0.50	0.46	3.63
9B7	9.47	26.97	40.08	56.32	61.81	79.75	49.74	29.98	21.43	26.92	14.75	11.43	36.61
11A6	0.09	0.61	0.93	1.11	1.49	0.41	1.00	0.30	0.24	0.19	0.16	0.10	0.49
11A7	0.03	0.29	0.26	0.14	0.17	0.06	0.09	0.06	0.05	0.05	0.04	0.03	0.21
14A2	3.54	7.21	10.96	8.16	5.12	2.64	4.10	3.83	3.59	3.29	2.68	2.18	6.75
14A3	0.16	0.56	1.02	0.93	0.50	0.15	0.26	0.15	0.11	0.08	0.05	0.06	0.39
Gauge ID	**November**	**December**	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**Annual**
14B2	1.18	6.21	12.27	18.07	13.60	4.22	3.30	2.21	1.78	1.38	1.59	1.11	5.77

14C2	4.13	4.62	5.09	5.14	6.35	6.27	5.81	6.01	6.50	5.25	4.69	4.17	5.01
14C8	1.38	3.47	5.09	5.88	7.20	5.20	3.10	2.17	2.16	1.54	1.05	1.26	3.24
14D1	32.52	37.29	60.89	125.69	114.67	60.53	61.93	46.74	40.35	36.50	26.43	24.81	66.43
15A4	0.04	0.99	1.21	1.34	1.28	0.42	0.63	0.54	0.28	0.20	0.15	0.13	0.51
15A8	0.40	1.82	5.85	9.69	6.08	2.67	2.36	1.41	1.19	0.93	0.75	0.58	2.47
16E6	7.79	10.83	13.15	13.76	15.56	20.50	18.27	16.84	15.97	14.36	11.50	10.33	15.47
16F1	1.17	1.56	1.79	2.23	3.34	4.43	4.77	3.02	2.29	1.83	1.28	1.22	2.36
16F2	9.98	15.35	23.64	26.39	41.63	53.92	48.24	32.22	25.64	18.53	13.36	10.36	26.36
17C6	0.72	1.61	2.98	3.17	5.01	5.40	3.70	2.59	1.76	1.40	1.03	0.73	2.46
17C10	0.24	0.33	0.53	0.78	1.44	1.73	1.54	0.90	0.69	0.56	0.48	0.43	0.81

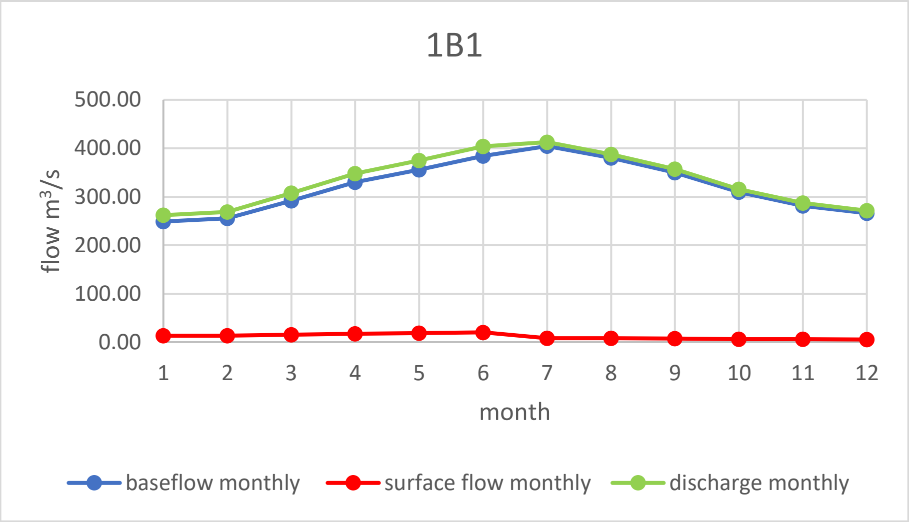
Appendix C: Total monthly average surface flow (m³/s) for each station

Table 3: Monthly average surface flow m³/s

Gauge ID	**November**	**December**	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**Annual**
1B1	13.10	13.43	15.37	17.39	18.73	20.21	8.25	7.75	7.14	6.32	5.75	5.42	10.03
1C1	1.31	2.48	4.56	6.14	3.72	2.04	0.54	0.39	0.37	0.32	0.28	0.27	2.20
1G1	37.41	48.99	63.75	75.85	79.84	72.28	19.24	18.12	16.45	14.48	12.43	11.59	41.39
1K1	3.08	2.68	11.25	17.91	16.46	3.64	0.49	0.26	0.17	0.16	0.07	0.01	6.26
1L12	44.56	47.83	55.42	61.42	63.62	60.74	26.71	25.58	22.72	22.47	21.15	20.56	47.61
1M1	1.53	3.66	4.76	4.31	5.11	3.11	0.59	0.48	0.40	0.34	0.26	0.28	1.94
1P2	30.12	32.92	40.72	49.08	50.93	54.80	30.18	27.45	24.56	21.97	19.38	16.61	32.83
1R3	2.45	12.39	25.84	37.63	31.95	10.53	0.50	0.27	0.24	0.18	0.14	0.12	9.67
1S7	0.18	0.98	2.01	5.32	4.17	1.01	0.12	0.07	0.05	0.04	0.03	0.01	1.04
2B22	0.82	3.24	4.25	6.45	3.91	1.60	0.26	0.21	0.18	0.15	0.15	0.15	1.84
2B33	1.34	8.40	8.11	13.53	7.49	1.57	0.17	0.11	0.09	0.07	0.07	0.05	2.88
2C3	0.11	0.37	0.84	0.92	0.90	0.74	0.11	0.06	0.04	0.03	0.02	0.01	0.35

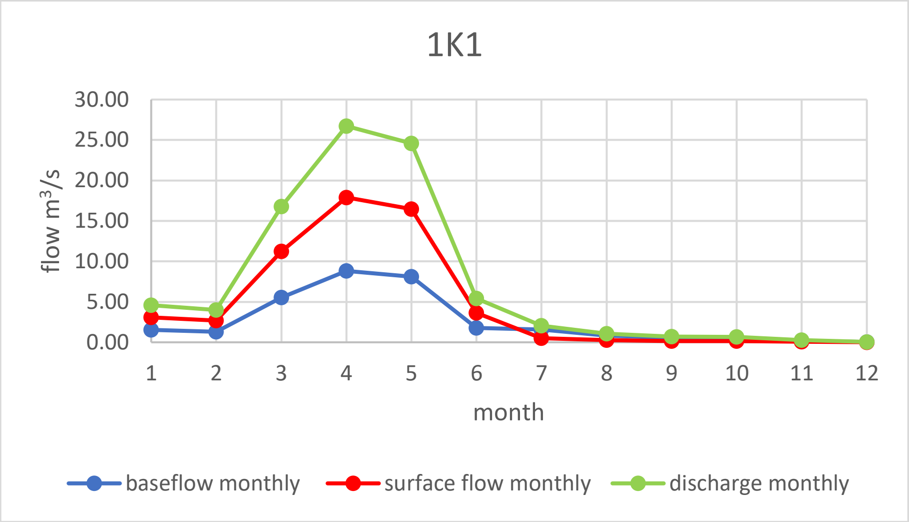
3E1	0.38	0.96	1.54	1.46	1.44	0.88	0.07	0.05	0.02	0.04	0.04	0.04	0.69
3E2	0.11	0.85	1.54	2.69	1.72	1.07	0.19	0.10	0.08	0.05	0.04	0.05	0.72
3E3	0.42	2.89	5.61	9.86	6.32	2.28	0.19	0.12	0.10	0.08	0.06	0.05	2.03
3E5	0.13	0.62	1.60	1.41	1.16	0.68	0.88	0.62	0.52	0.41	0.33	0.22	0.66
3F3	0.43	1.28	2.32	2.94	2.71	1.61	0.17	0.12	0.10	0.08	0.09	0.05	0.86
4B1	3.55	31.88	80.72	119.87	99.01	46.64	6.59	2.34	1.81	1.30	0.86	0.49	32.50
4B3	0.20	5.74	6.23	11.89	7.48	2.30	0.14	0.06	0.04	0.02	0.01	0.01	2.53
4B4	0.51	3.29	9.05	13.49	11.27	5.24	0.50	0.25	0.18	0.12	0.05	0.04	3.44
4B9	1.40	20.75	38.33	50.82	56.59	24.12	1.84	0.95	0.73	0.53	0.31	0.23	16.56
4C2	2.53	14.13	33.06	40.44	31.64	15.01	0.90	0.60	0.49	0.39	0.26	0.19	11.48
4C11	1.87	7.04	28.97	33.39	36.29	4.26	0.34	0.26	0.14	0.08	0.04	0.02	10.41
4D4	0.37	1.66	4.51	7.56	6.75	3.28	0.33	0.18	0.16	0.09	0.06	0.04	2.37
4D24	0.36	1.31	3.04	3.85	3.65	2.79	0.40	0.23	0.16	0.12	0.10	0.12	1.29
4E2	0.47	2.28	5.13	6.95	5.00	1.47	0.15	0.08	0.09	0.07	0.06	0.05	1.99
5C1	4.25	12.75	25.54	41.92	46.50	31.51	3.27	2.28	1.91	1.71	1.33	0.98	16.02
Gauge ID	**November**	**December**	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**Annual**
5D1	1.58	5.91	18.38	29.43	26.87	12.55	0.92	0.24	0.13	0.08	0.04	0.12	7.95
5D2	0.03	1.54	9.68	29.37	38.84	20.45	3.04	0.89	0.47	0.23	0.08	0.03	10.53
5D3	0.26	0.91	1.57	2.09	1.95	1.09	0.24	0.21	0.20	0.18	0.13	0.09	0.85
5E6	0.14	0.32	0.88	0.96	1.11	0.53	0.06	0.04	0.03	0.03	0.02	0.02	0.47
5F1	0.01	0.18	2.12	5.10	5.90	3.02	0.58	0.13	0.07	0.04	0.02	0.01	1.54
6C1	0.02	1.77	9.10	24.90	27.31	6.51	0.18	0.05	0.03	0.01	0.00	0.00	8.50
6C5	0.08	0.43	1.32	1.99	3.04	0.76	0.13	0.07	0.04	0.02	0.02	0.00	0.78
6D10	0.90	13.37	30.55	38.53	42.95	24.02	3.31	1.73	1.12	0.79	0.38	0.19	15.45
7A3	0.38	4.08	25.87	42.73	37.16	13.01	1.02	0.48	0.31	0.18	0.09	0.04	10.22

7D8	0.77	1.88	4.32	3.82	4.04	4.06	0.59	0.42	0.33	0.23	0.15	0.11	1.61
7E2	0.79	12.05	34.89	58.92	52.14	17.33	3.72	1.55	1.16	0.64	0.26	0.08	14.15
7F1	0.62	1.19	2.41	4.13	5.68	3.64	0.31	0.22	0.17	0.14	0.11	0.09	1.47
7F2	0.53	1.03	1.84	2.10	2.66	2.82	0.26	0.19	0.15	0.12	0.09	0.07	1.02
7G14	1.29	3.42	11.32	17.27	19.40	14.10	0.77	0.47	0.37	0.29	0.21	0.17	5.97
7G18	1.97	5.87	19.61	29.39	28.80	22.22	0.99	0.66	0.49	0.39	0.27	0.19	6.95
7H1	0.84	1.32	1.89	2.19	2.86	3.02	0.19	0.15	0.12	0.10	0.08	0.07	1.22
7H2	0.34	0.47	0.57	0.64	0.86	1.09	0.16	0.12	0.10	0.09	0.08	0.07	0.36
7H3	3.20	7.33	11.97	14.97	17.36	22.07	2.16	1.26	1.02	0.87	0.45	0.52	7.79
8A5	3.78	7.76	11.11	16.02	23.53	11.89	1.09	0.73	0.72	0.71	0.67	0.70	7.55
9A2	1.83	5.94	11.17	12.46	17.41	12.94	0.92	0.57	0.43	0.33	0.26	0.20	4.14
9A4	0.31	1.57	3.47	6.03	4.15	2.38	0.19	0.15	0.12	0.09	0.07	005	1.23
9A5	0.23	0.51	0.69	0.82	1.15	0.99	0.11	0.08	0.06	0.05	0.04	0.03	0.43
9B3	2.03	0.98	4.50	5.29	4.75	2.37	0.23	0.16	0.09	0.06	0.12	0.85	3.37
9B5	0.08	0.58	1.98	4.09	2.12	0.72	0.08	0.04	0.03	0.02	0.01	0.01	1.43
9B6	0.63	3.19	7.64	14.35	12.95	5.92	0.15	0.09	0.07	0.05	0.03	0.03	3.63
9B7	7.44	21.19	31.49	44.25	48.57	62.66	8.10	4.88	3.49	2.75	2.40	1.86	20.59
11A6	0.16	1.09	1.65	1.98	2.64	0.73	0.15	0.05	0.04	0.03	0.02	0.02	0.62
11A7	0.06	051	0.47	0.25	0.31	0.11	0.01	0.01	0.01	0.01	0.00	0.00	0.25
14A2	6.02	12.27	18.65	13.89	8.72	4.49	0.61	0.57	0.54	0.49	0.40	0.33	8.94
14A3	0.55	1.87	3.41	3.12	1.67	0.51	0.06	0.03	0.03	0.02	0.01	0.01	1.05
Gauge ID	**November**	**December**	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**Annual**
14B2	2.29	12.06	23.82	35.08	26.40	8.19	1.16	0.78	0.62	0.48	0.56	0.39	10.26
14C2	4.66	5.21	5.74	5.80	7.16	7.07	6.05	6.25	6.77	5.47	4.88	4.34	5.88
14C8	2.34	5.91	8.66	10.00	12.26	8.86	2.75	1.93	1.91	1.36	0.93	1.12	4.86



14D1	57.82	66.29	108.19	223.46	203.85	107.62	26.54	20.03	17.29	15.64	11.33	10.63	88.06
15A4	0.19	4.30	5.50	6.09	5.84	1.93	0.25	0.21	0.11	0.08	0.06	0.05	2.85
15A8	0.55	2.52	8.08	13.38	8.40	3.69	0.12	0.07	0.06	0.05	0.04	0.03	2.57
16E6	3.18	4.42	5.36	5.62	6.36	8.37	1.81	1.67	1.58	1.42	1.14	1.02	4.36
16F1	0.92	1.23	1.41	1.75	2.62	3.48	0.78	0.49	0.37	0.30	0.21	0.20	1.16
16F2	4.48	6.90	10.62	11.86	18.70	24.23	5.36	3.58	2.85	2.06	1.48	1.15	8.32
17C6	0.18	0.40	0.74	0.79	1.25	1.35	0.28	0.19	0.13	0.11	0.08	0.06	0.43
17C10	0.17	0.27	0.43	0.61	1.18	1.42	0.15	0.09	0.07	0.06	0.05	0.04	0.35

Appendix D: Hydrographs for each river station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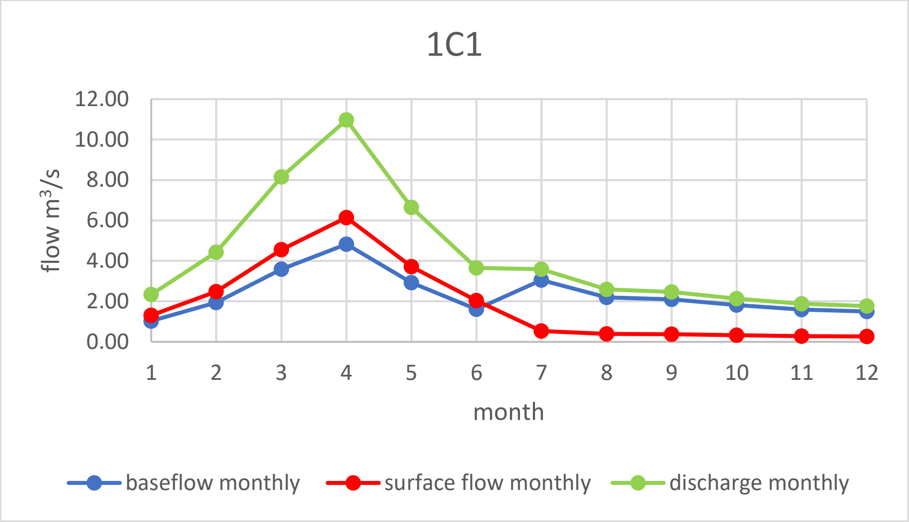
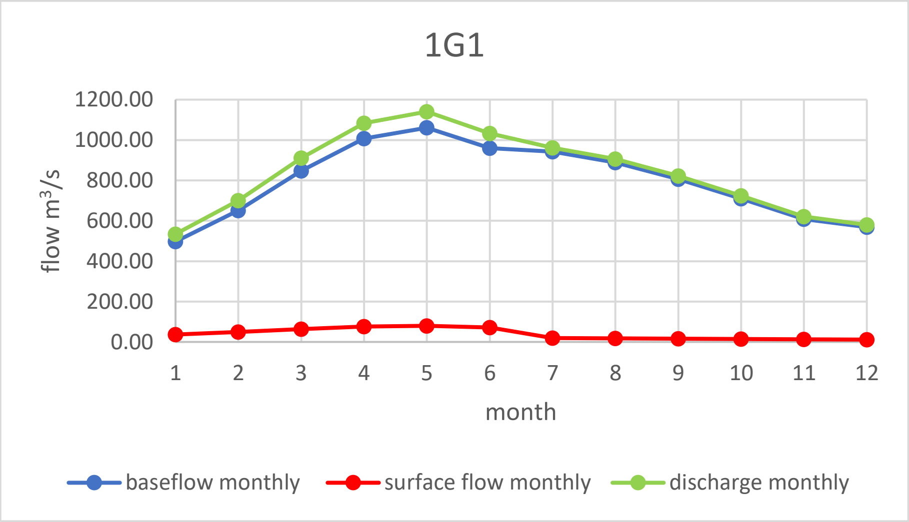
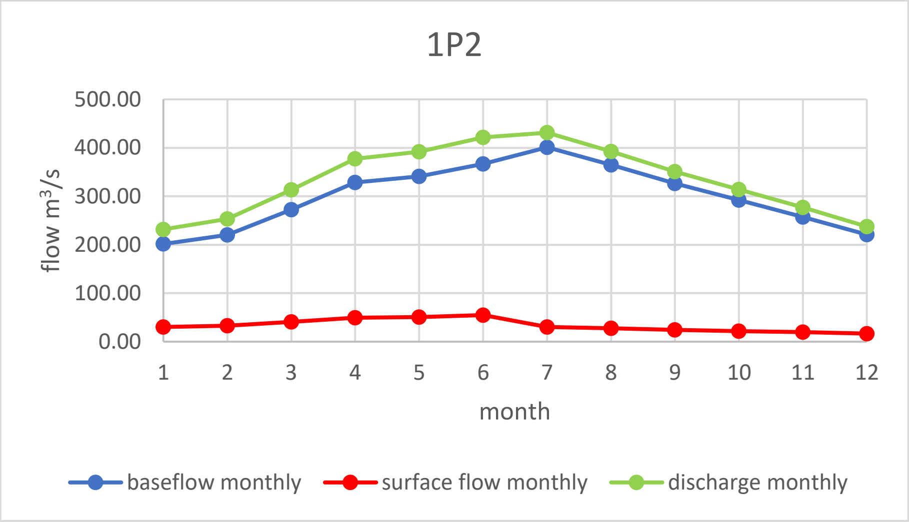
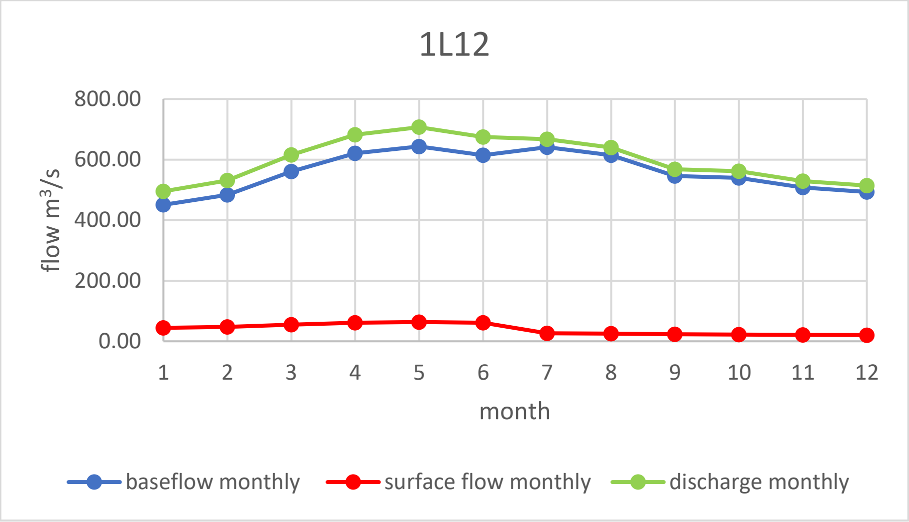
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly


1C1
flow m3/s
12.00
10.00
8.00
6.00
4.00
2.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly


1G1
flow m3/s
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly


1P2
flow m³/s
500.00
400.00
300.00
200.00
100.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly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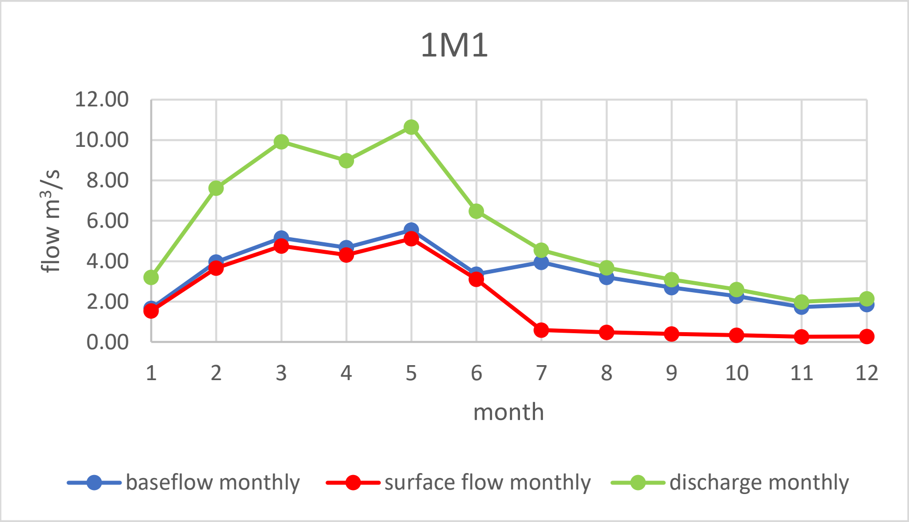
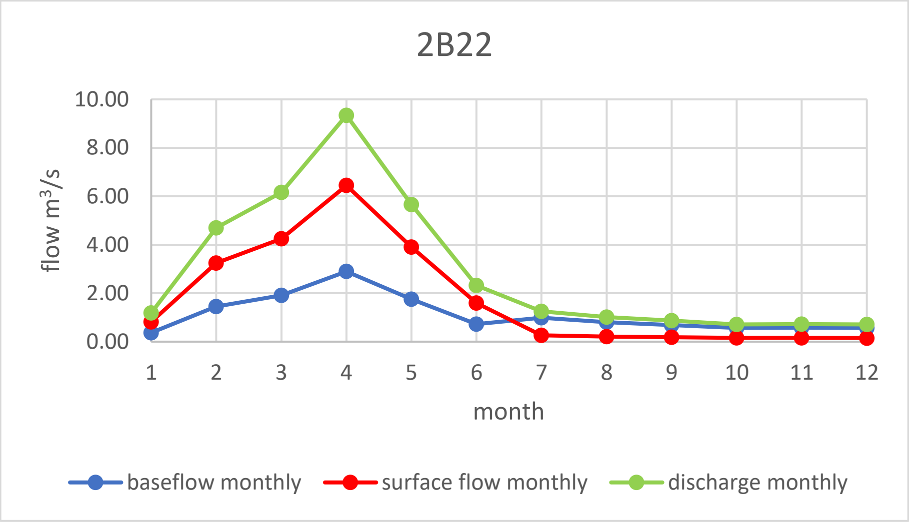
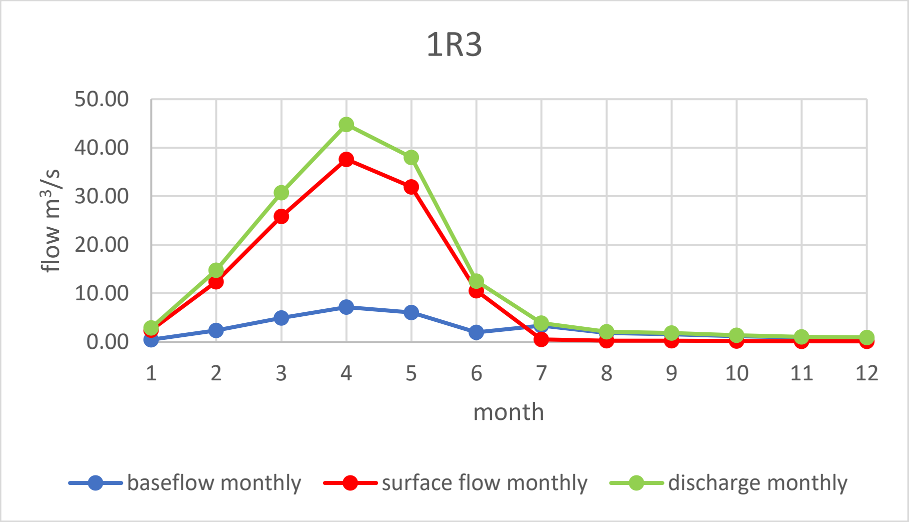
flow m³/s
800.00
600.00
400.00
200.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly


1M1
flow m³/s
12.00
10.00
8.00
6.00
4.00
2.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly


2B22
flow m³/s
10.00
8.00
6.00
4.00
2.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly


1R3
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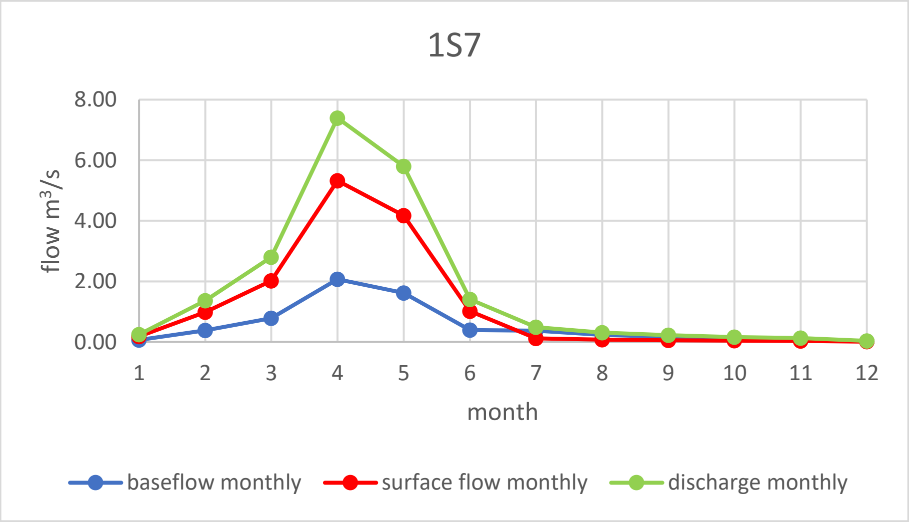
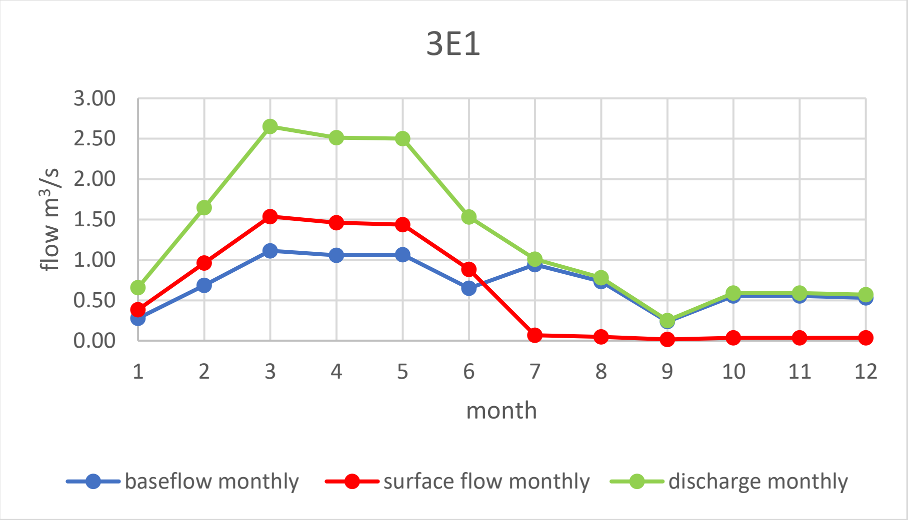
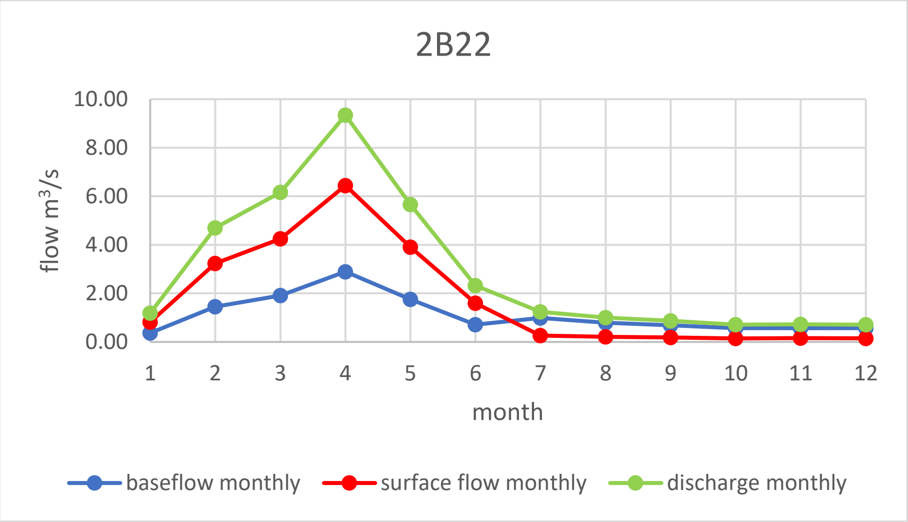
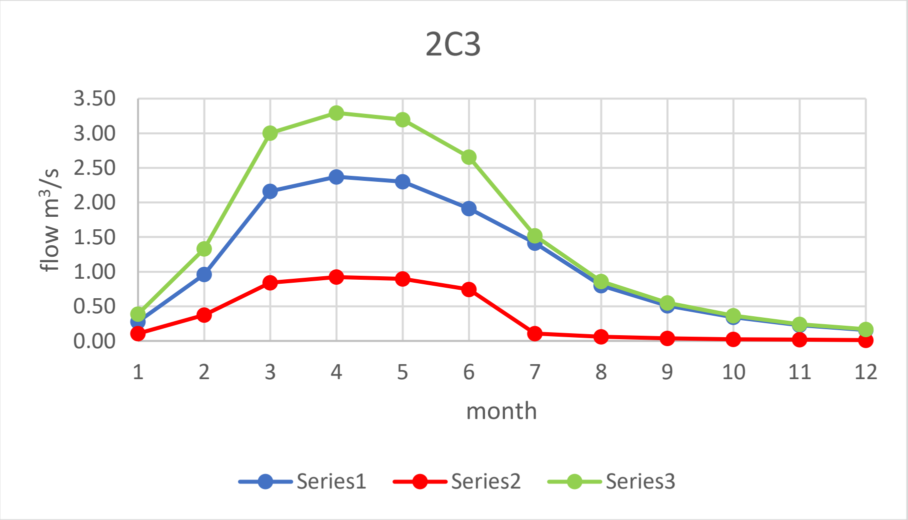
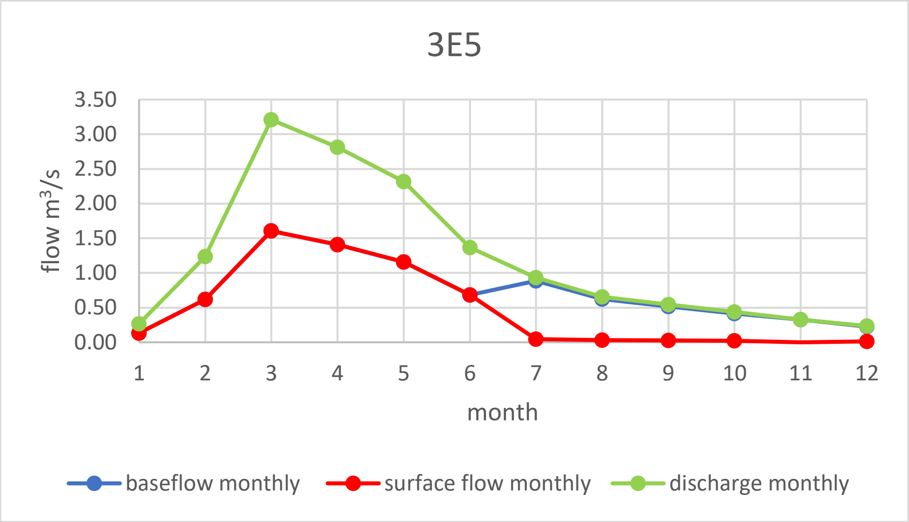
50.00
40.00
30.00
20.00
10.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

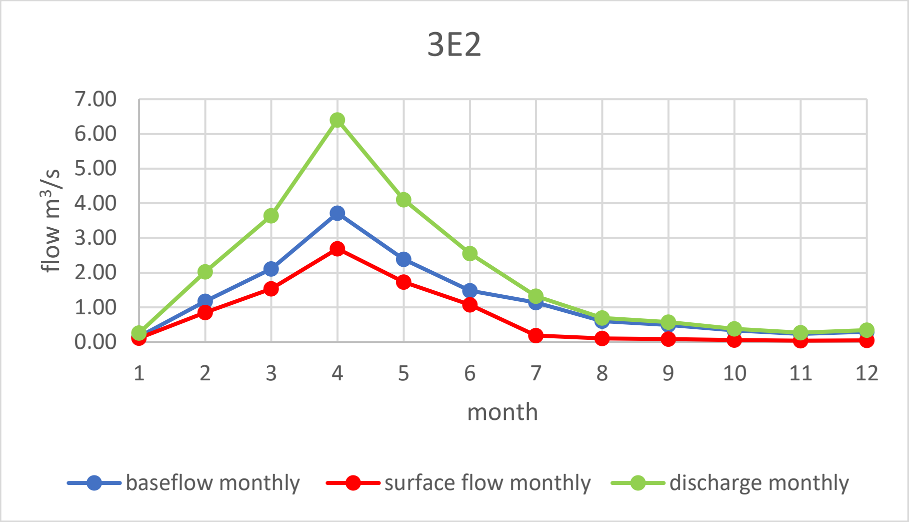

1S7
flow m³/s
8.00
6.00
4.00
2.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

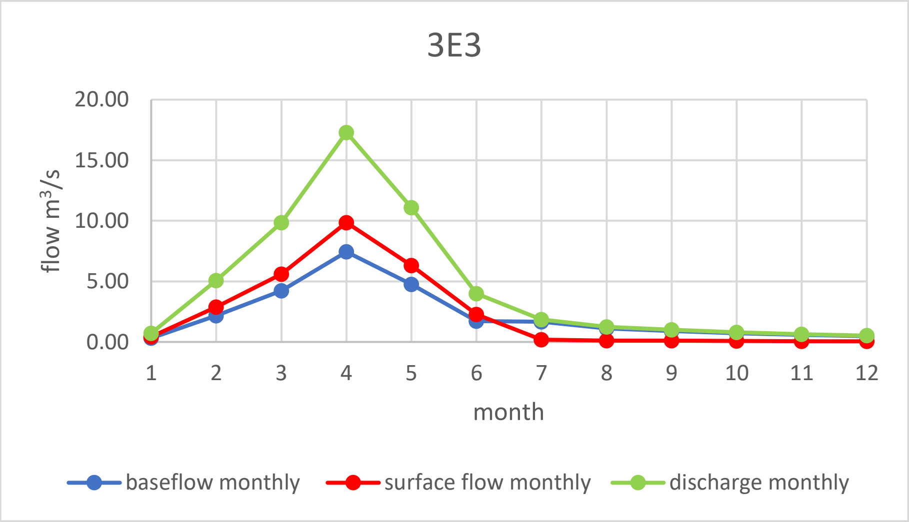

3E1
flow m³/s
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

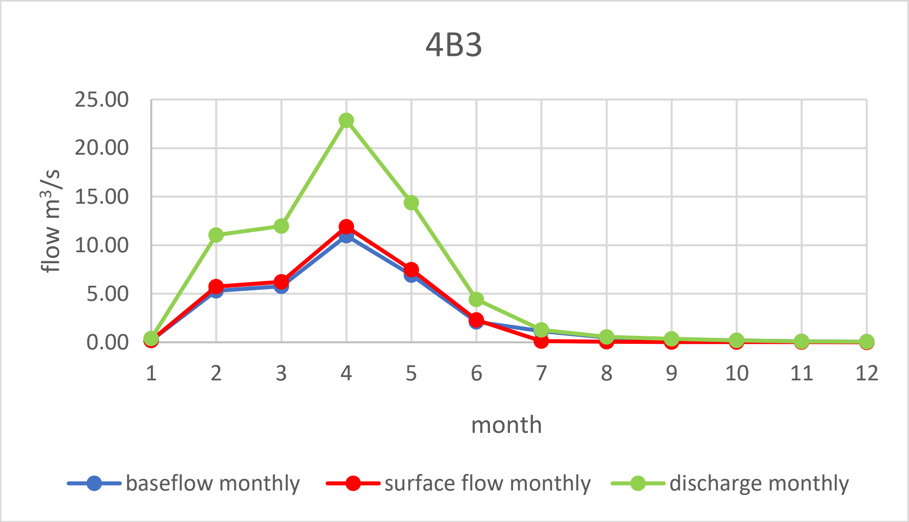

2B22
flow m³/s
10.00
8.00
6.00
4.00
2.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

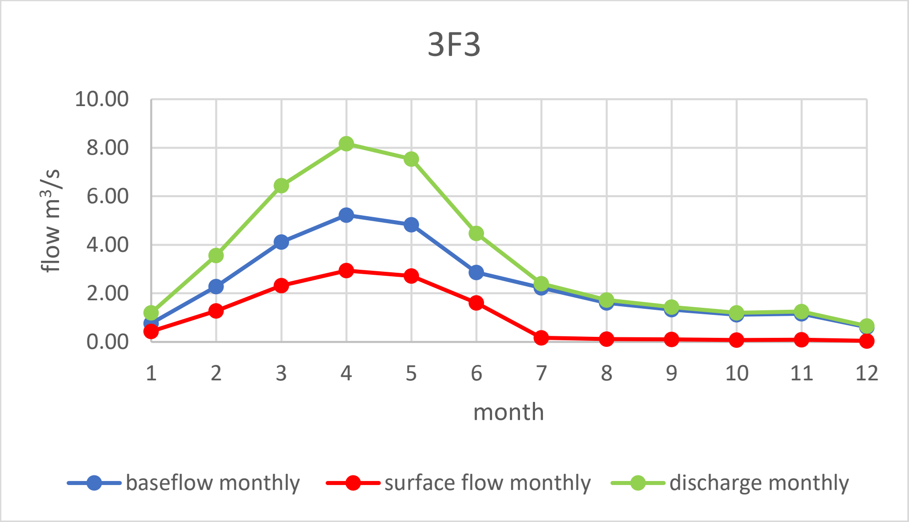

2C3
flow m³/s
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
Series1
Series2
Series3

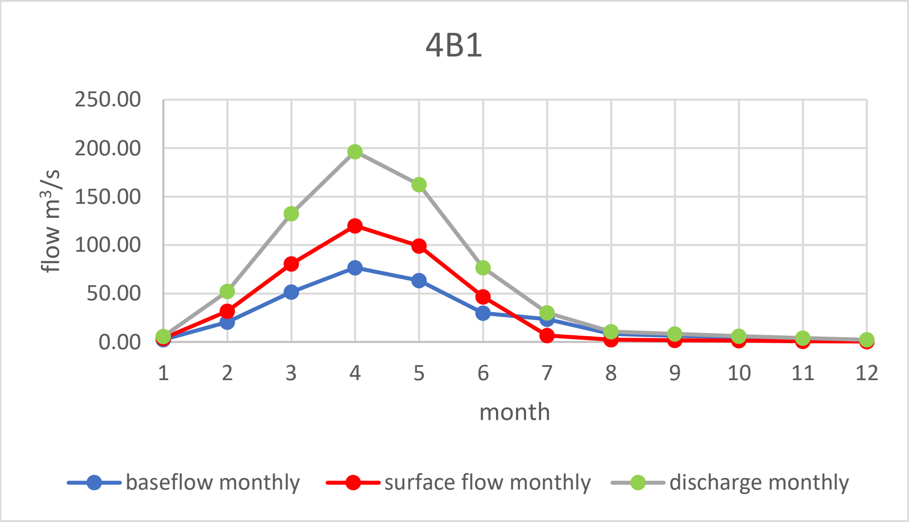

3E5
flow m3/s
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

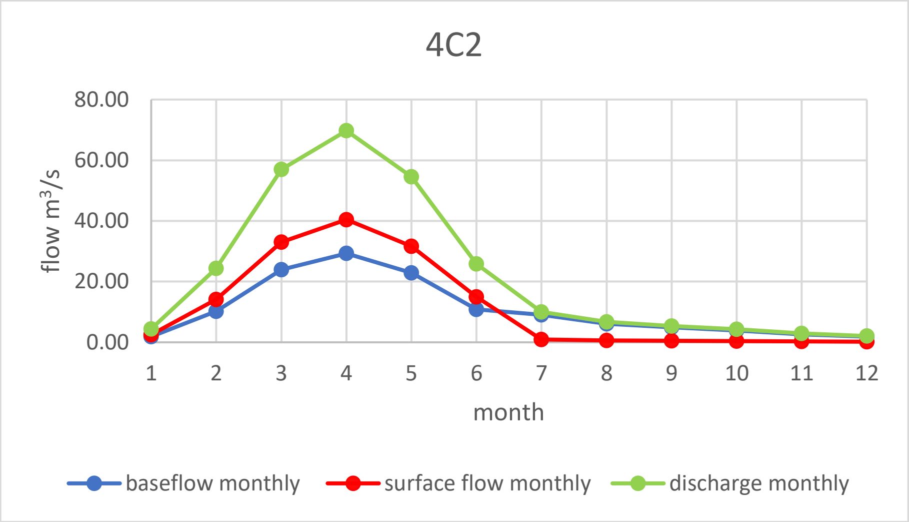

3E2
flow m3/s
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

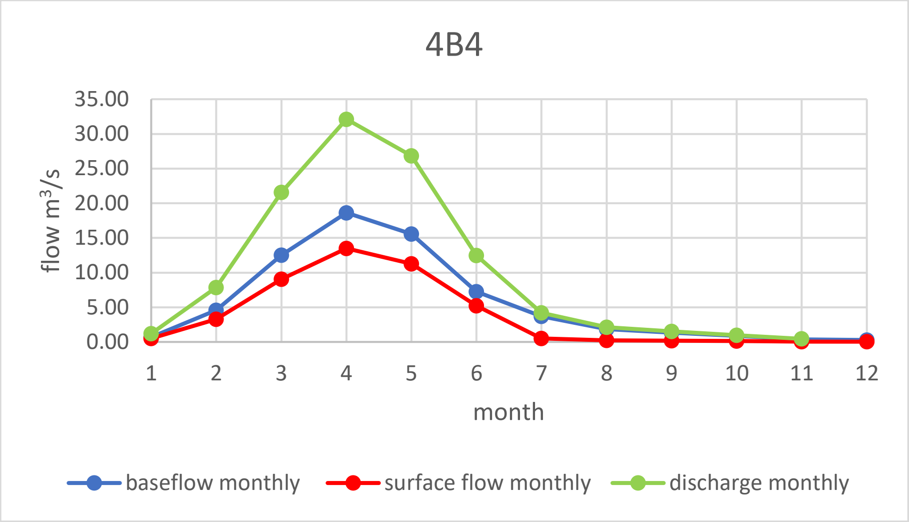

3E3
flow m3/s
20.00
15.00
10.00
5.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

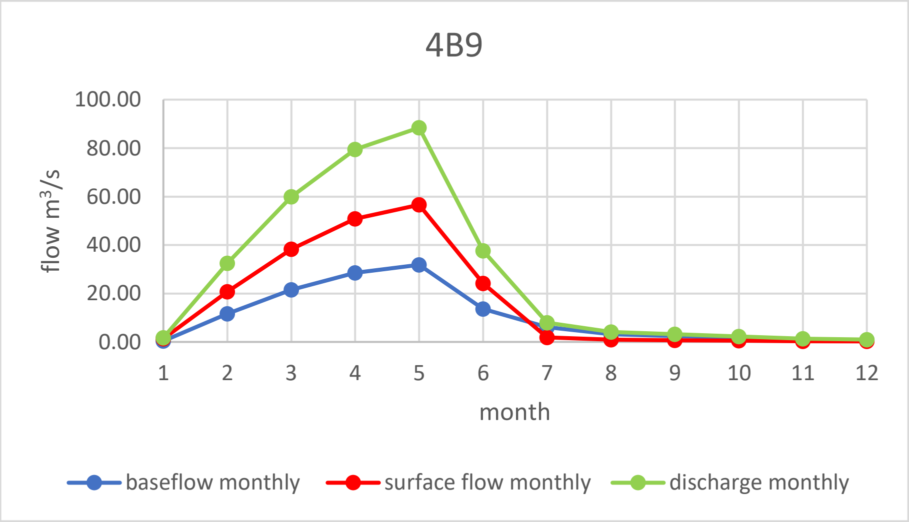

4B3
flow m³/s
25.00
20.00
15.00
10.00
5.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

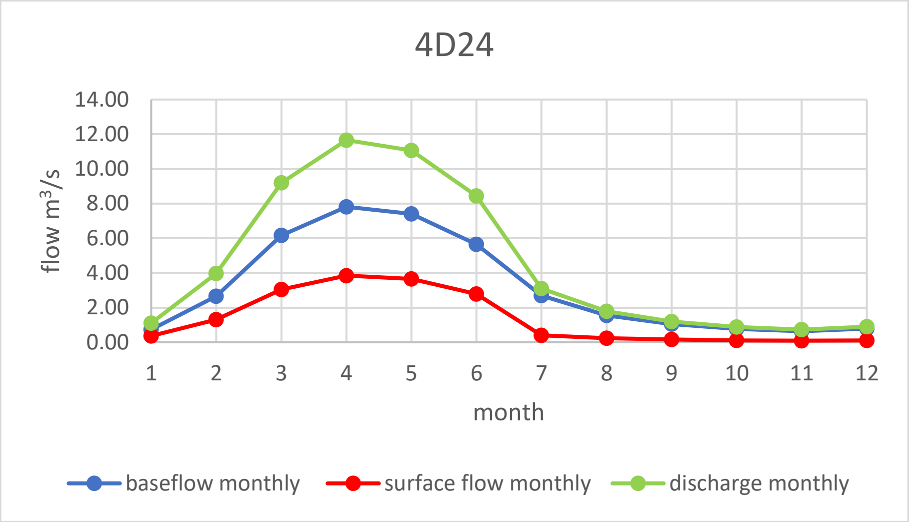

3F3
flow m³/s
10.00
8.00
6.00
4.00
2.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

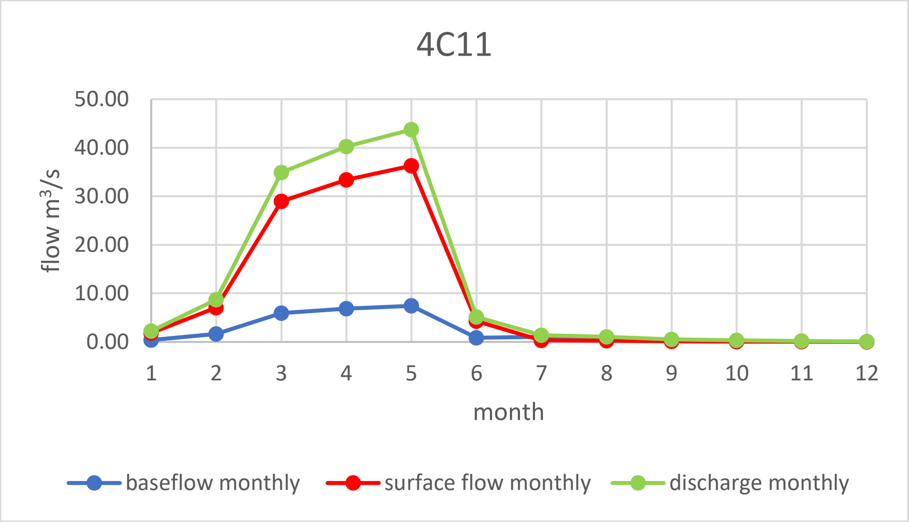

4B1
flow m³/s
250.00
200.00
150.00
100.00
50.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

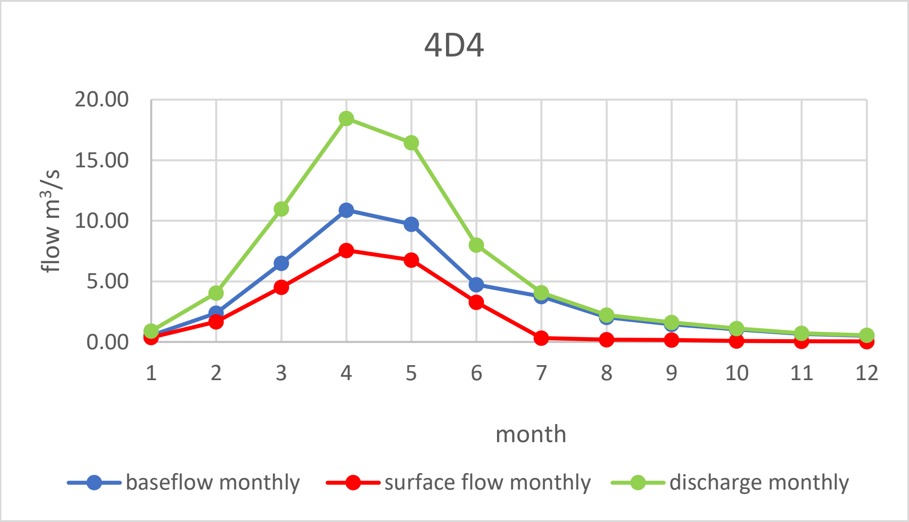

4C2
flow m³/s
80.00
60.00
40.00
20.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

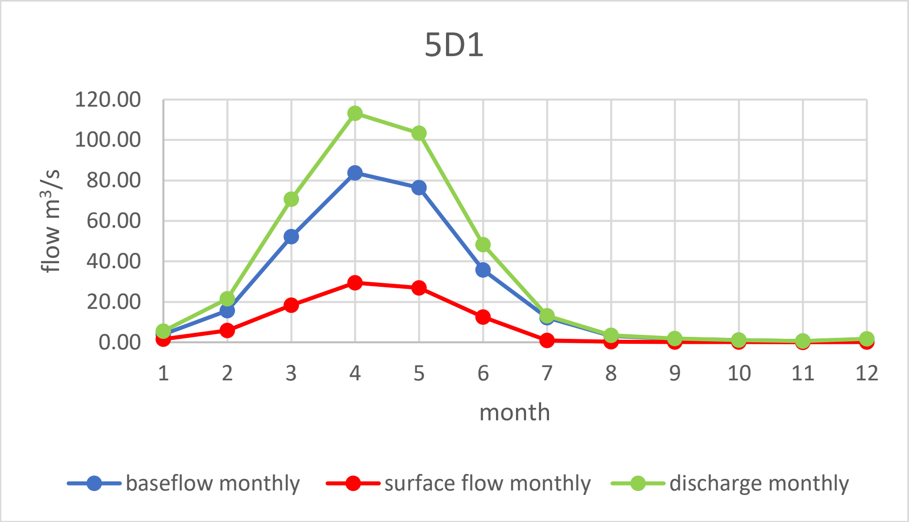

4B4
flow m³/s
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

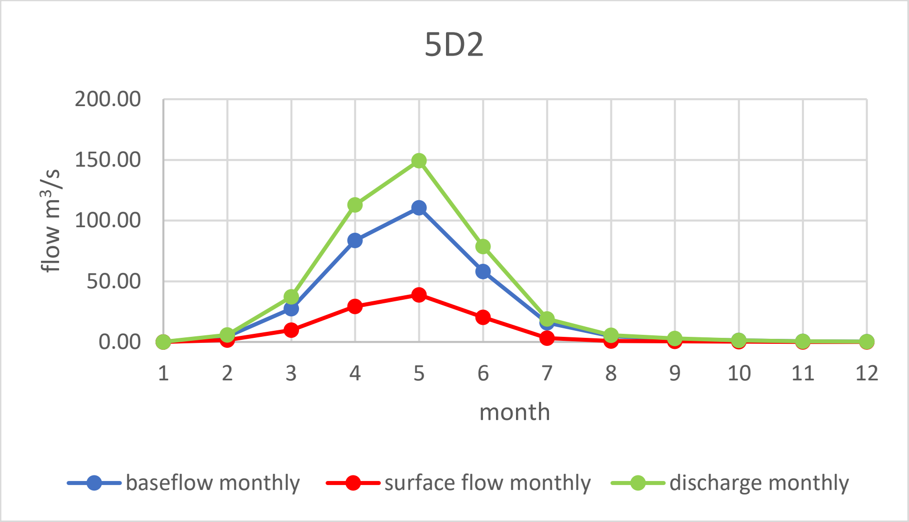

4B9
flow m³/s
100.00
80.00
60.00
40.00
20.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

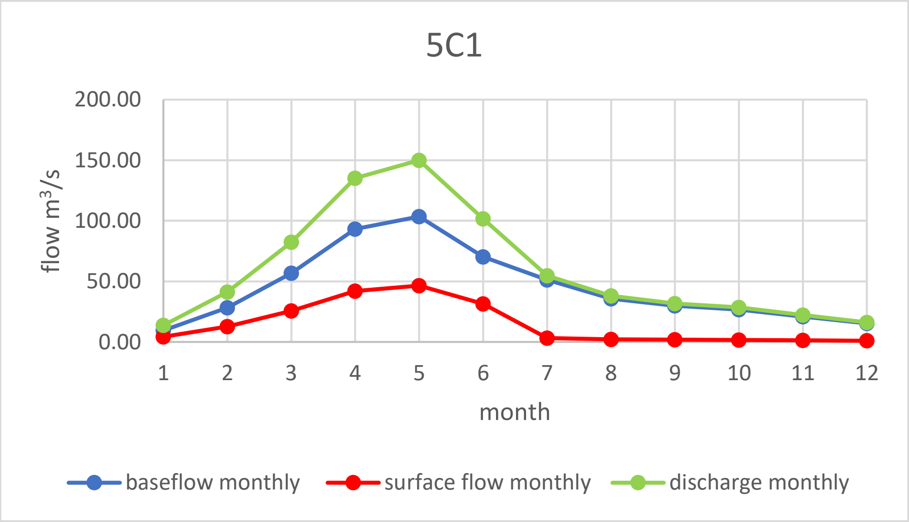

4D24
flow m³/s
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

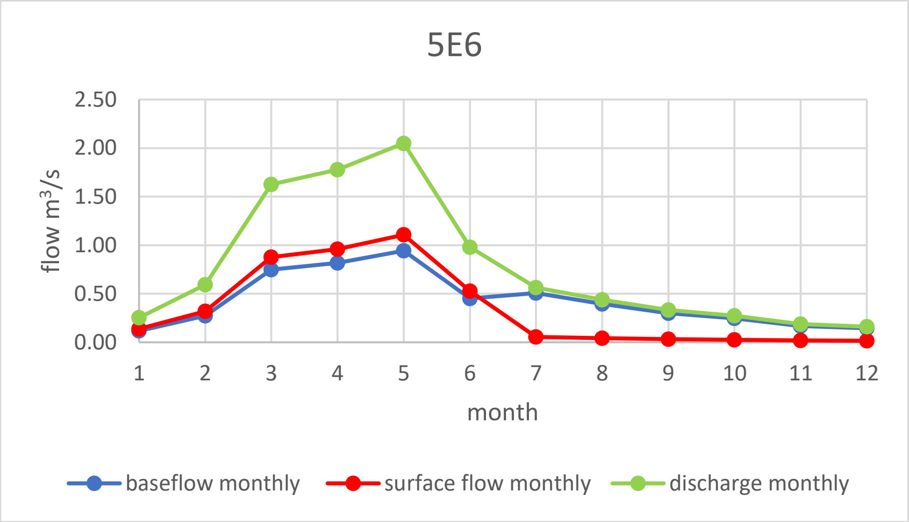

4C11
flow m³/s
50.00
40.00
30.00
20.00
10.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

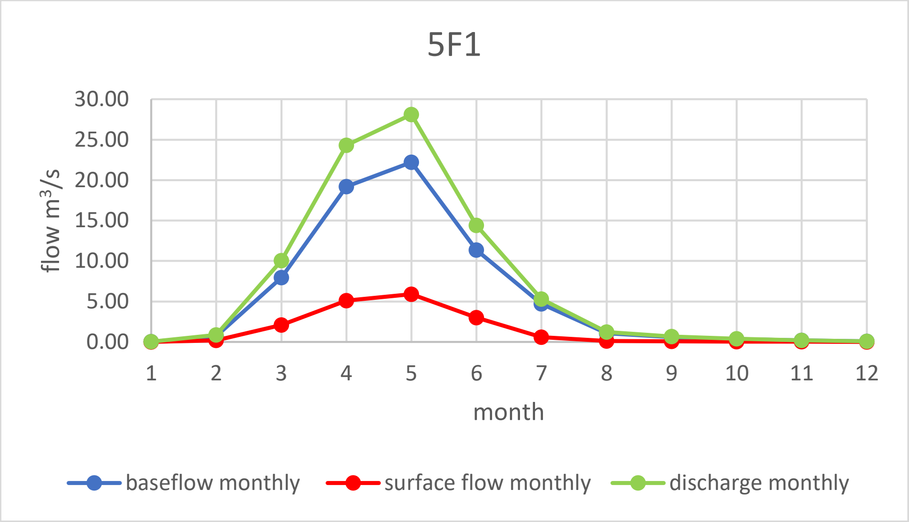

4D4
flow m³/s
20.00
15.00
10.00
5.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

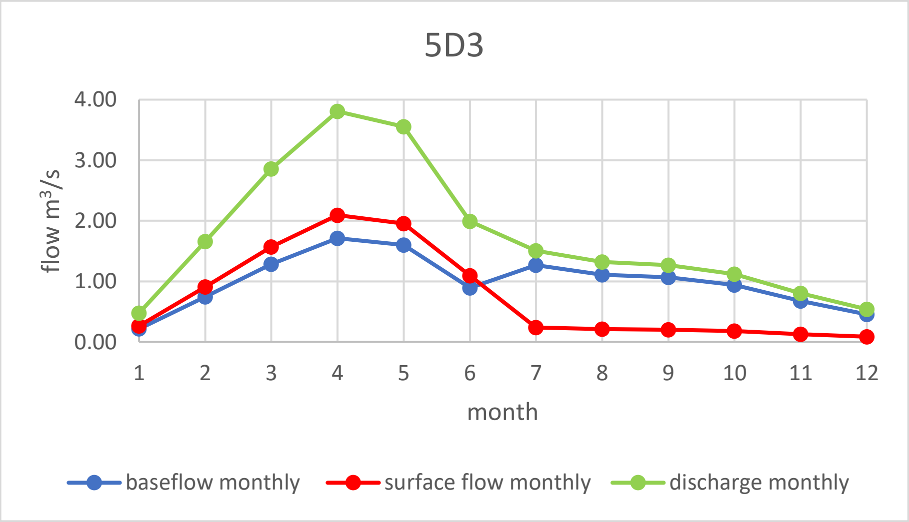

5D1
120.00
100.00
80.00
60.00
40.00
20.00
0.00
flow m³/s
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

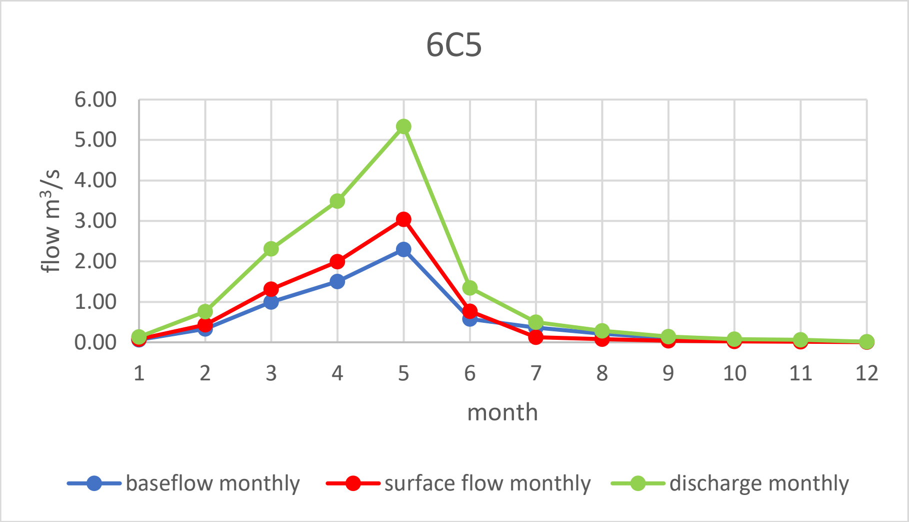

5D2
200.00
150.00
100.00
50.00
0.00
flow m³/s
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

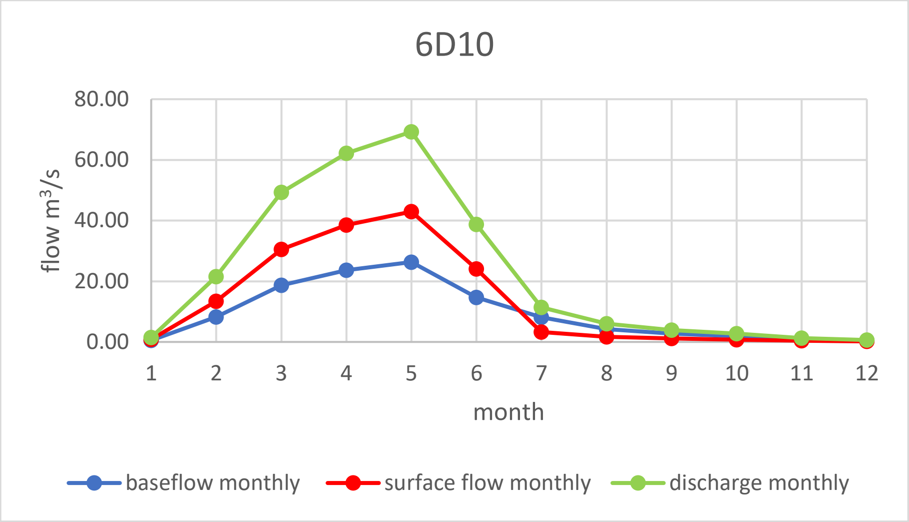

5C1
200.00
150.00
100.00
50.00
0.00
flow m³/s
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

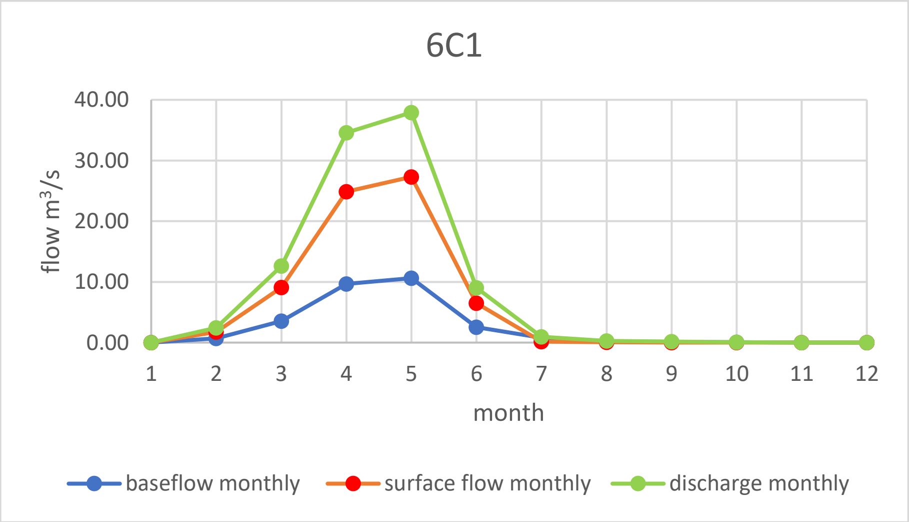

5E6
2.50
2.00
1.50
1.00
0.50
0.00
flow m³/s
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

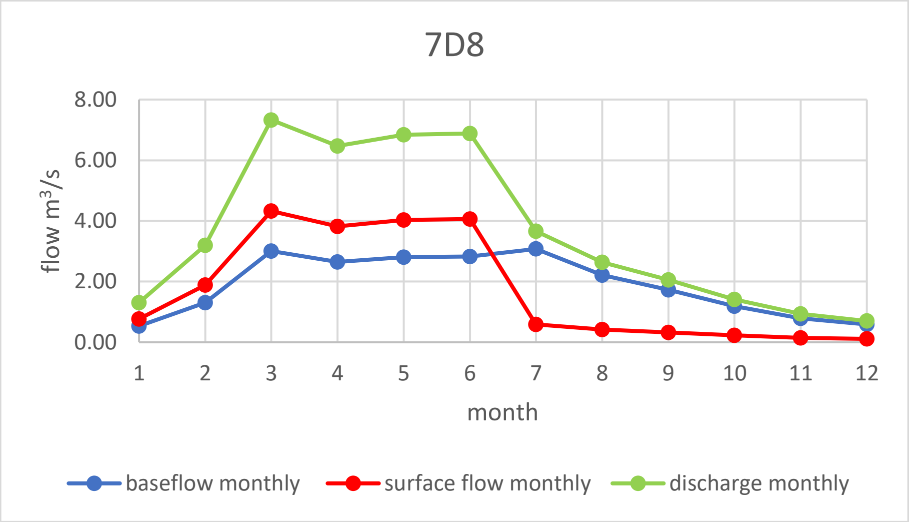

5F1
30.00
25.00
20.00
15.00
10.00
5.00
0.00
flow m³/s
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

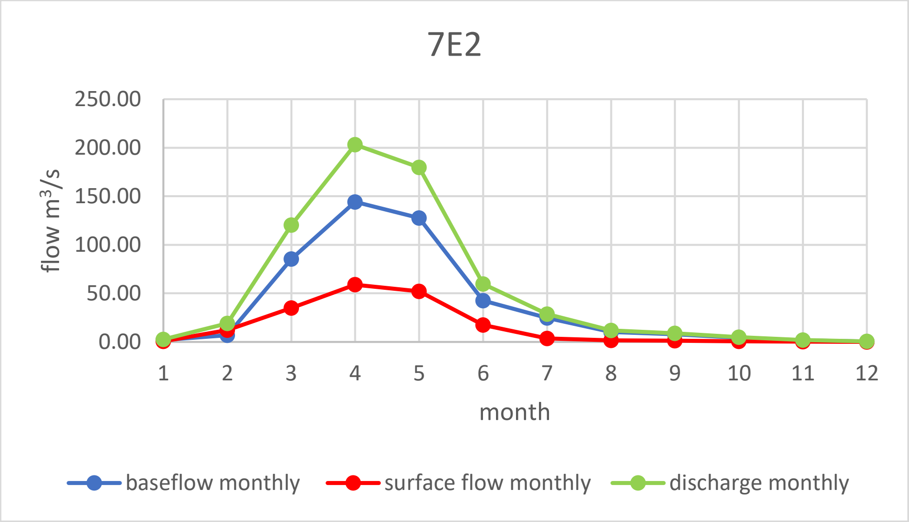

5D3
4.00
3.00
2.00
1.00
0.00
flow m³/s
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

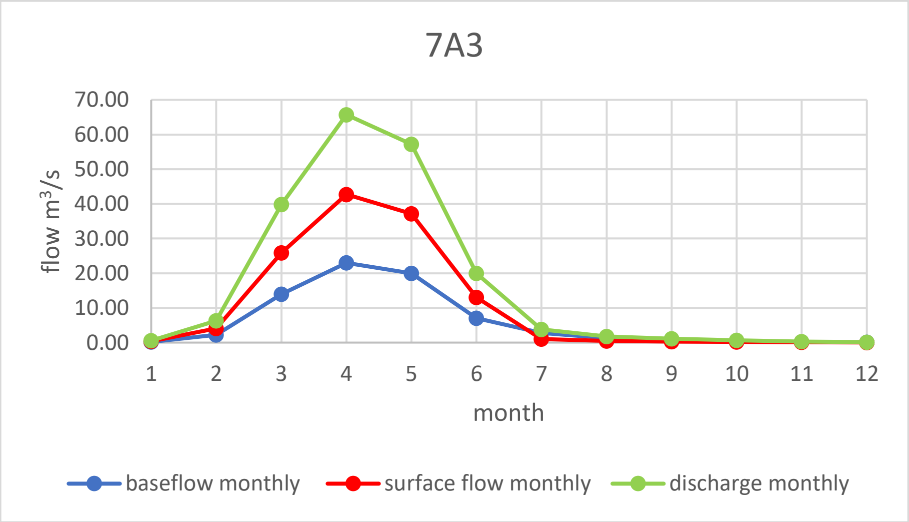

6C5
6.00
5.00
4.00
3.00
2.00
1.00
0.00
flow m³/s
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

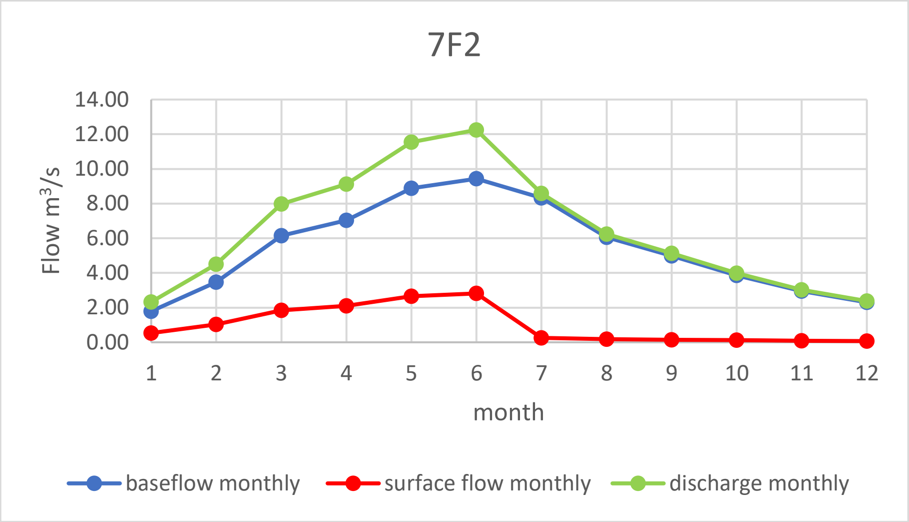

6D10
80.00
60.00
40.00
20.00
0.00
flow m³/s
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

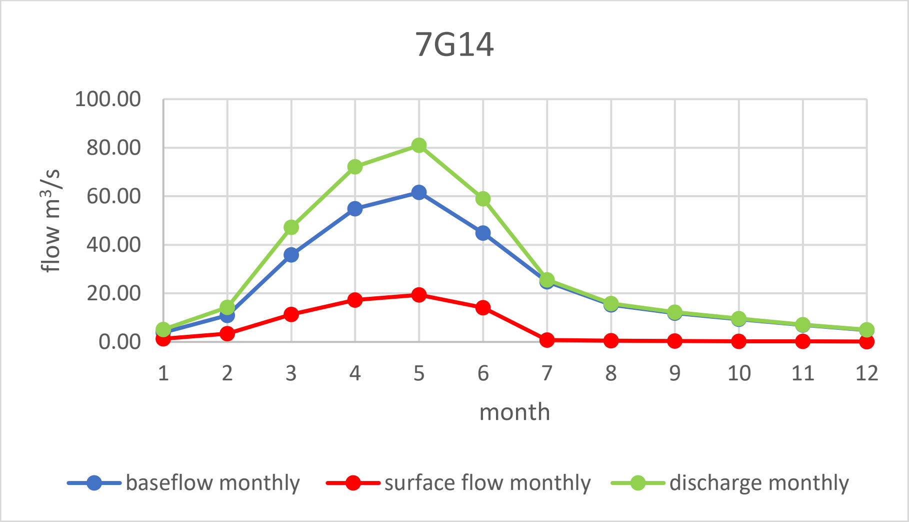

6C1
40.00
30.00
20.00
10.00
0.00
flow m³/s
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

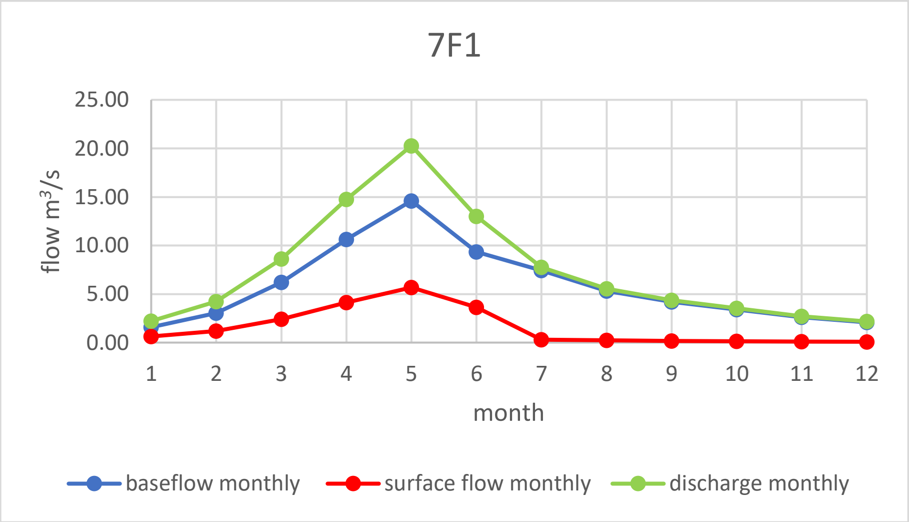

7D8
8.00
6.00
4.00
2.00
0.00
flow m³/s
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

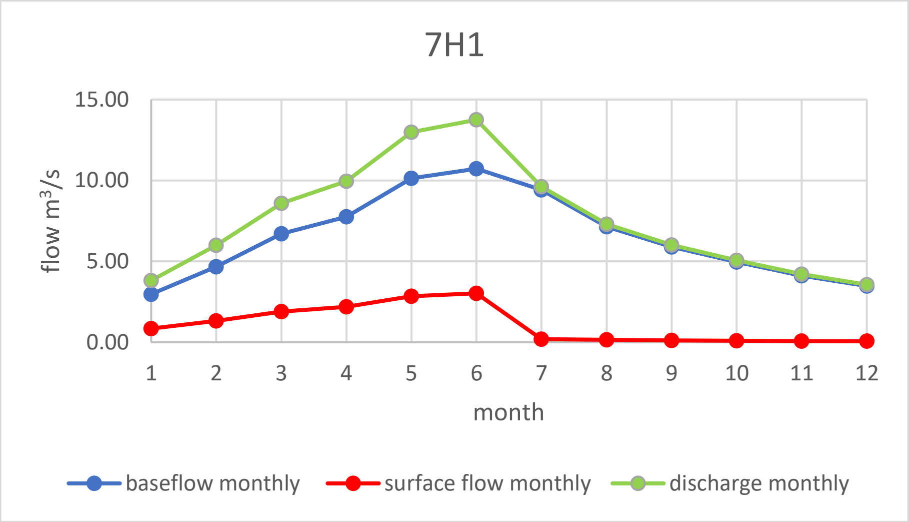

7E2
250.00
200.00
150.00
100.00
50.00
0.00
flow m³/s
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

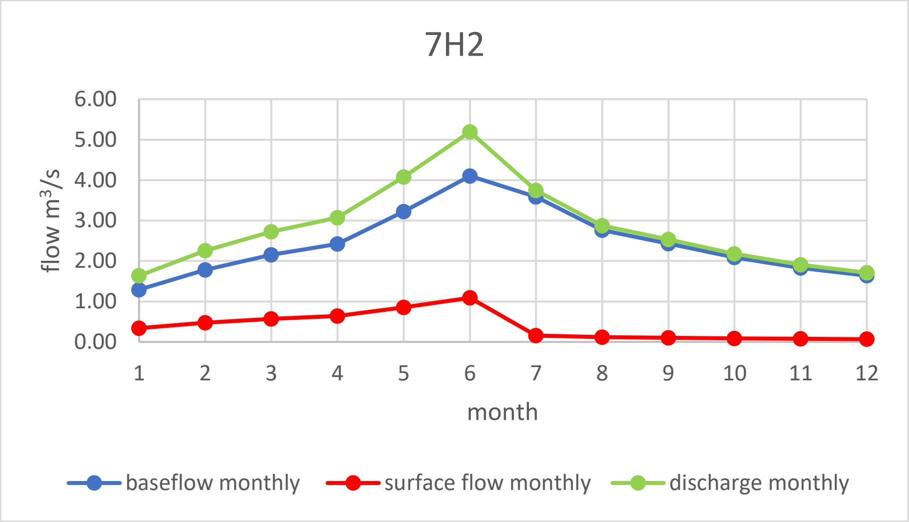

7A3
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
flow m³/s
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

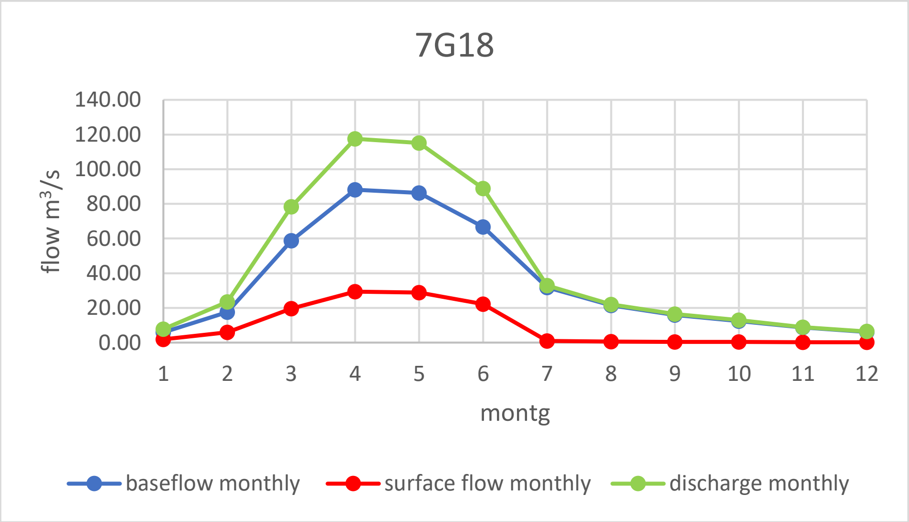

7F2
Flow m3/s
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

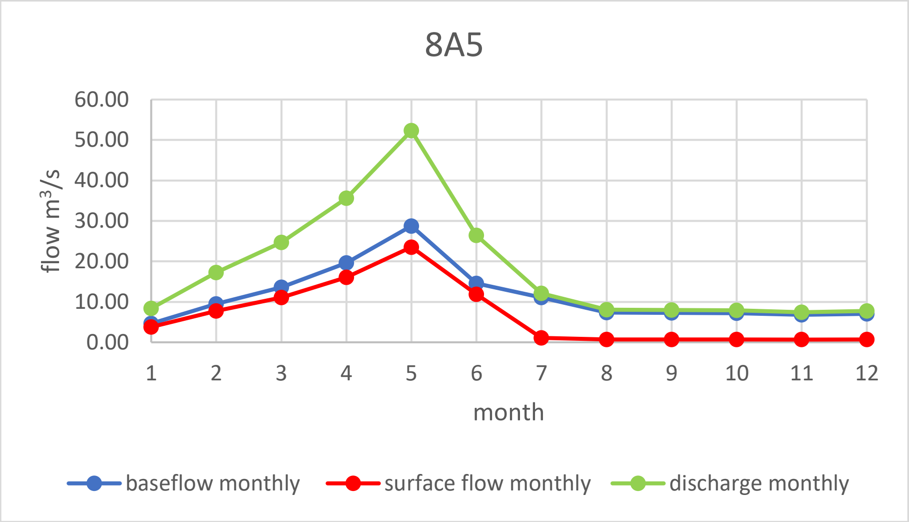

7G14
flow m3/s
100.00
80.00
60.00
40.00
20.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

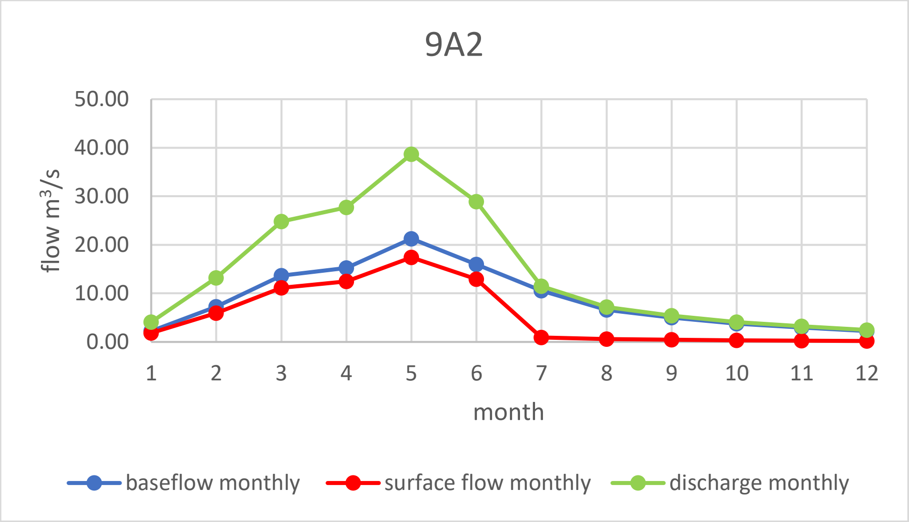

7F1
flow m3/s
25.00
20.00
15.00
10.00
5.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

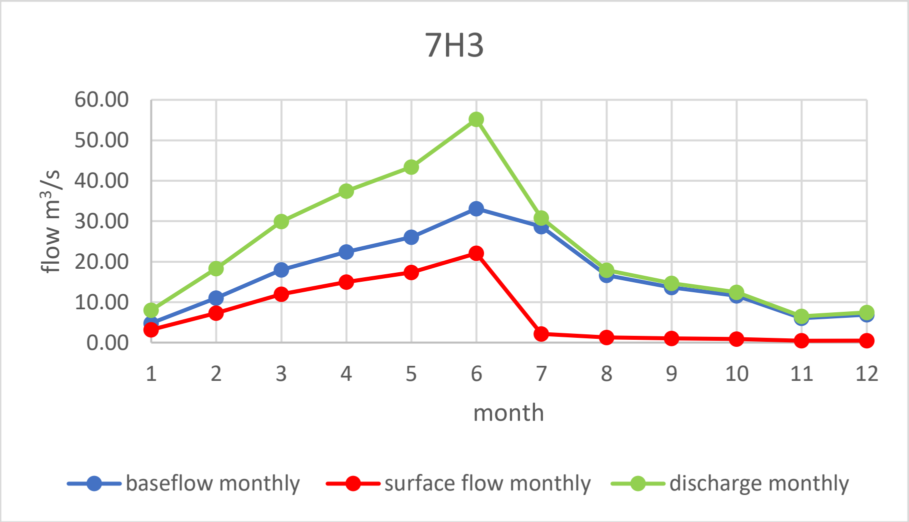

7H1
flow m³/s
15.00
10.00
5.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

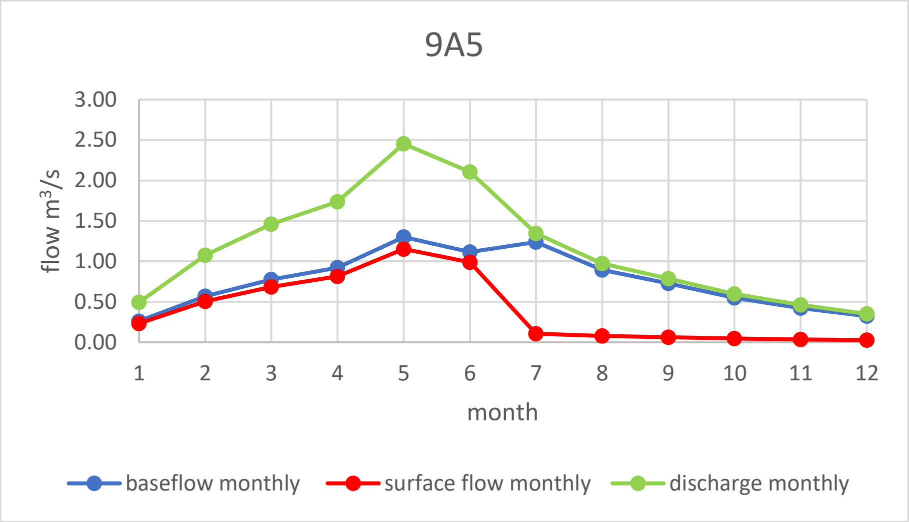

7H2
flow m³/s
6.00
5.00
4.00
3.00
2.00
1.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

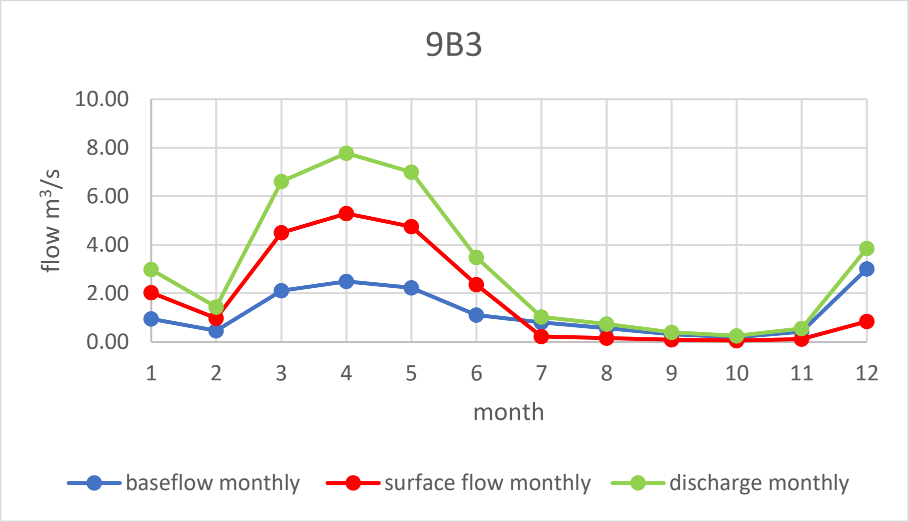

7G18
flow m³/s
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
montg
baseflow monthly
surface flow monthly
discharge monthly

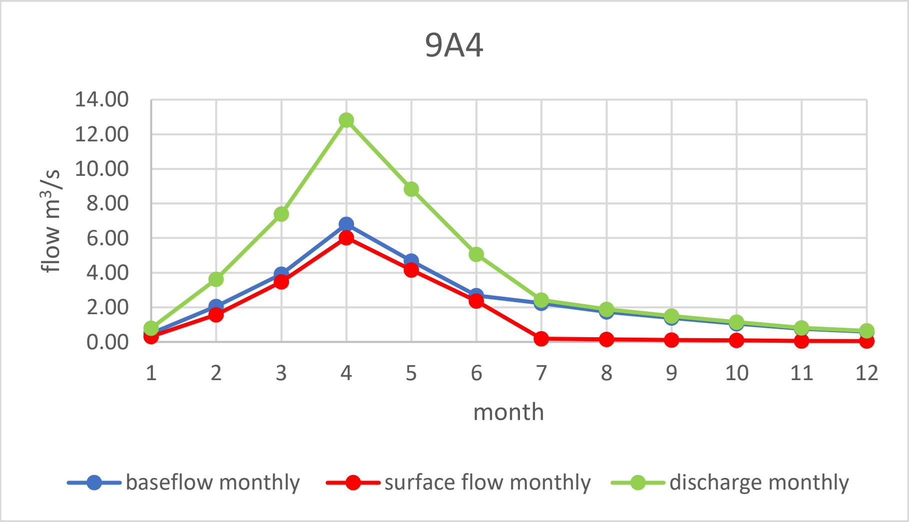

8A5
flow m^3/s
60.00
50.00
40.00
30.00
20.00
10.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

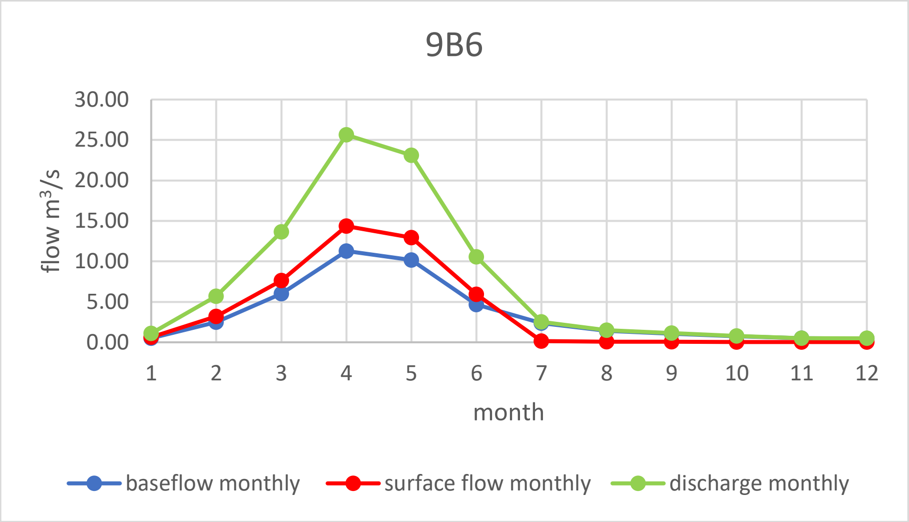

9A2
flow m^3/s
50.00
40.00
30.00
20.00
10.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

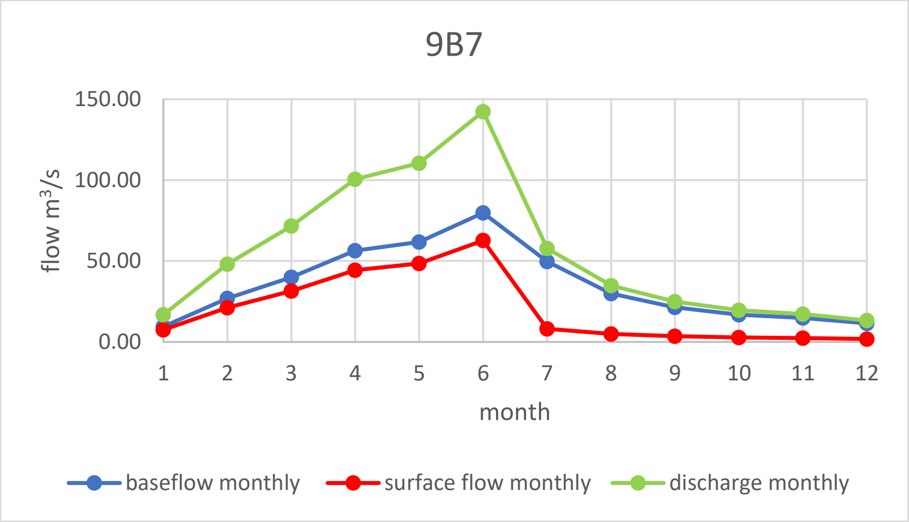

7H3
flow m^3/s
60.00
50.00
40.00
30.00
20.00
10.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

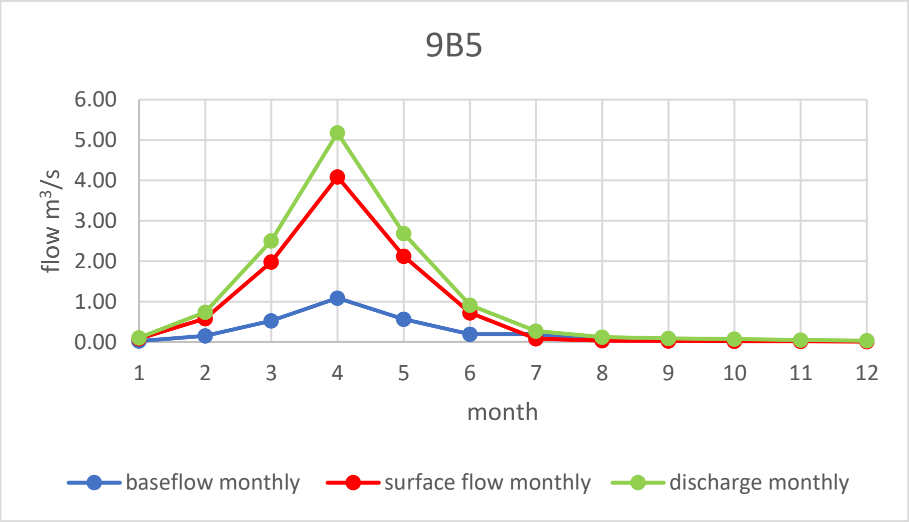

9A5
flow m³/s
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

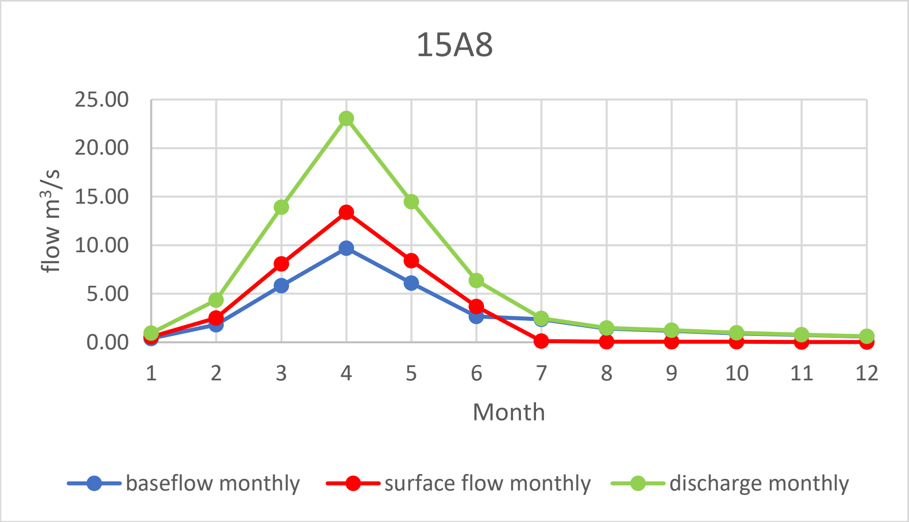

9B3
flow m³/s
10.00
8.00
6.00
4.00
2.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

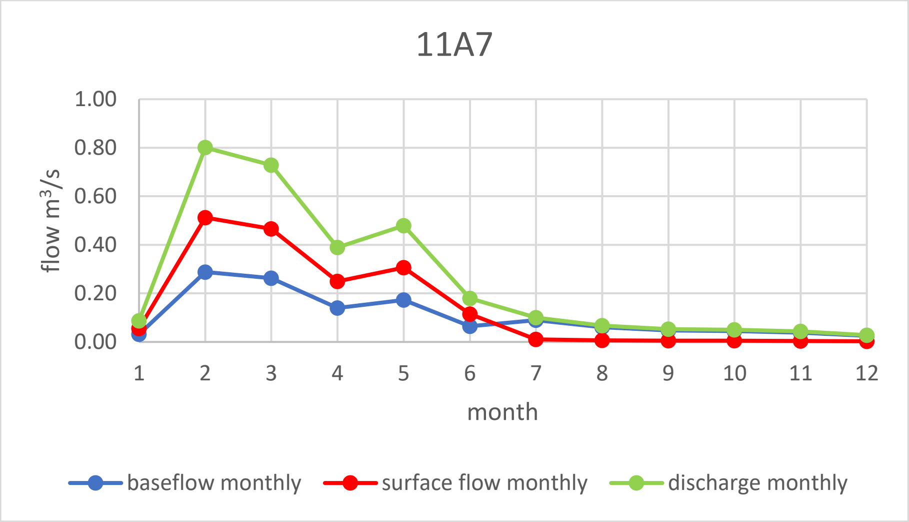

9A4
flow m³/s
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

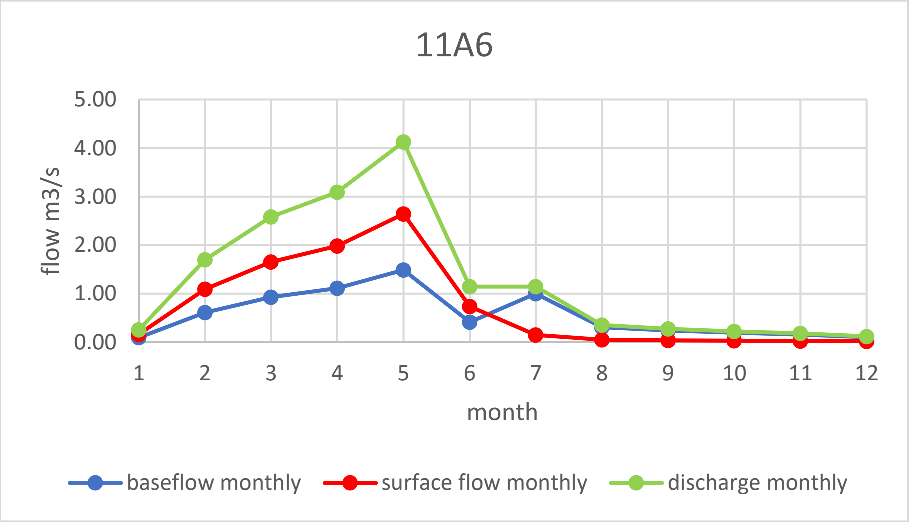

9B6
30.00
25.00
20.00
15.00
10.00
5.00
0.00
flow m³/s
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

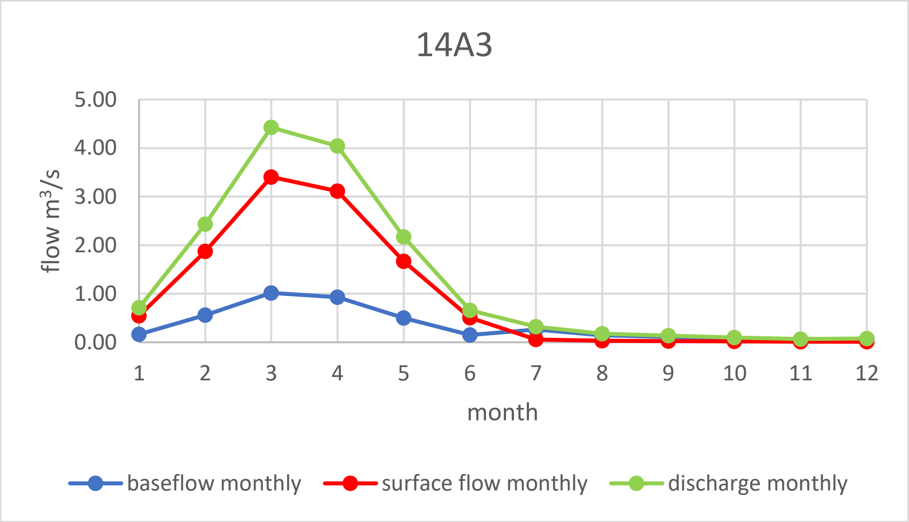

9B7
150.00
100.00
50.00
0.00
flow m³/s
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

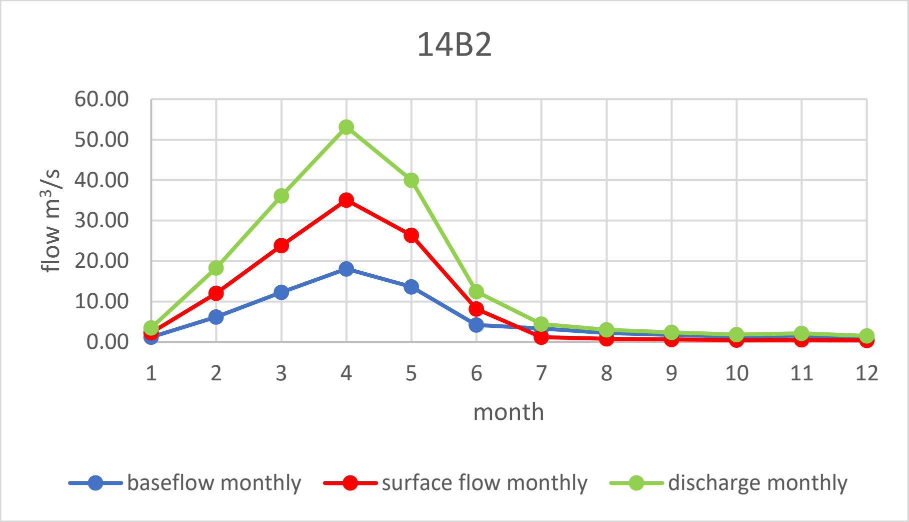

9B5
6.00
5.00
4.00
3.00
2.00
1.00
0.00
flow m³/s
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

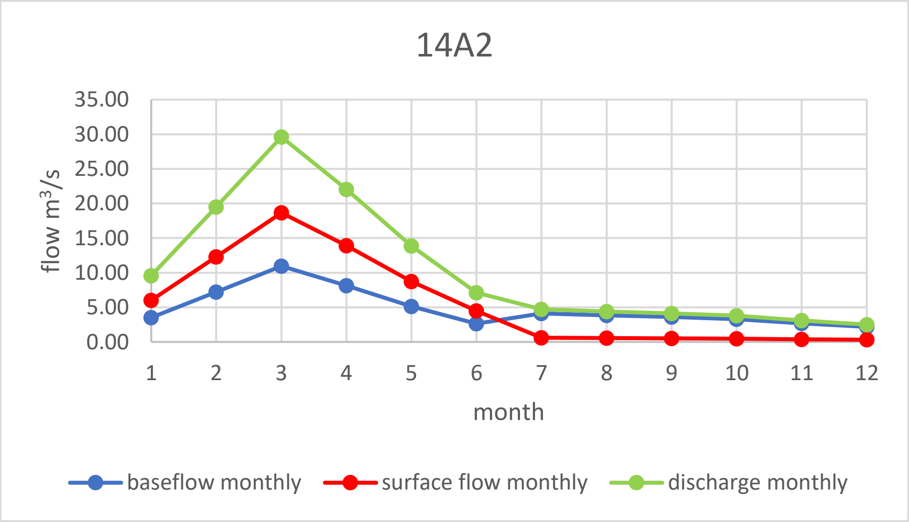

15A8
flow m3/s
25.00
20.00
15.00
10.00
5.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
Month
baseflow monthly
surface flow monthly
discharge monthly

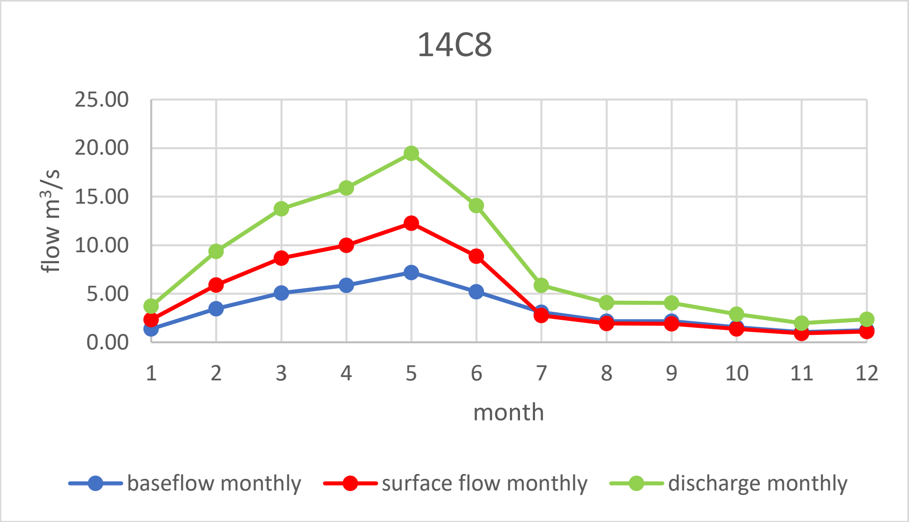

11A7
flow m3/s
1.00
0.80
0.60
0.40
0.20
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

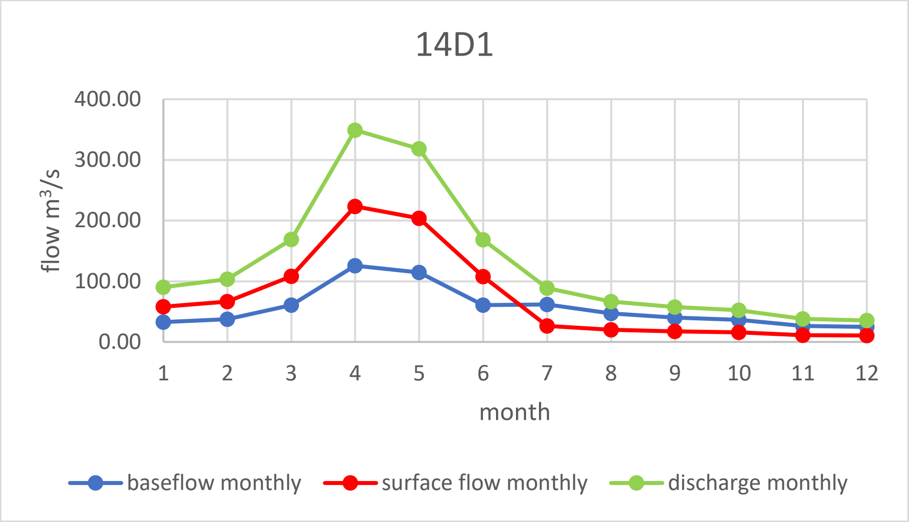

11A6
flow m3/s
5.00
4.00
3.00
2.00
1.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

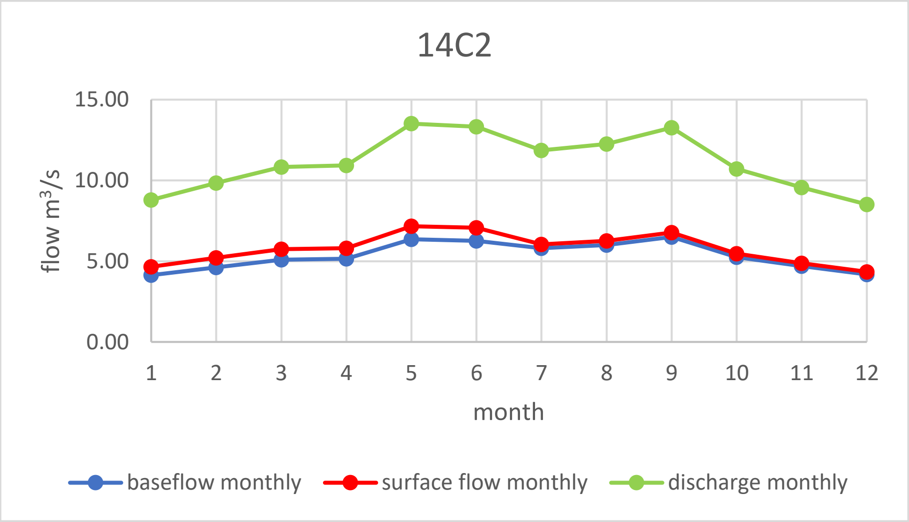

14A3
flow m³/s
5.00
4.00
3.00
2.00
1.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

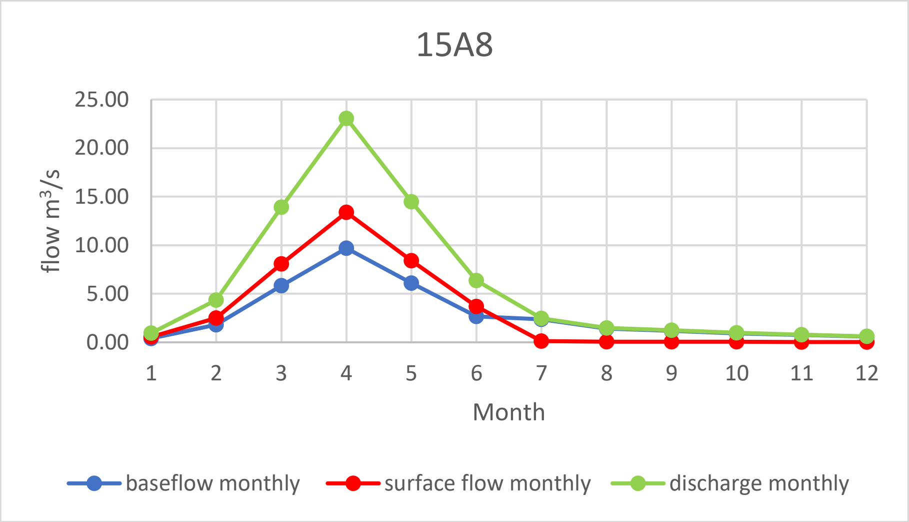

14B2
flow m³/s
60.00
50.00
40.00
30.00
20.00
10.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

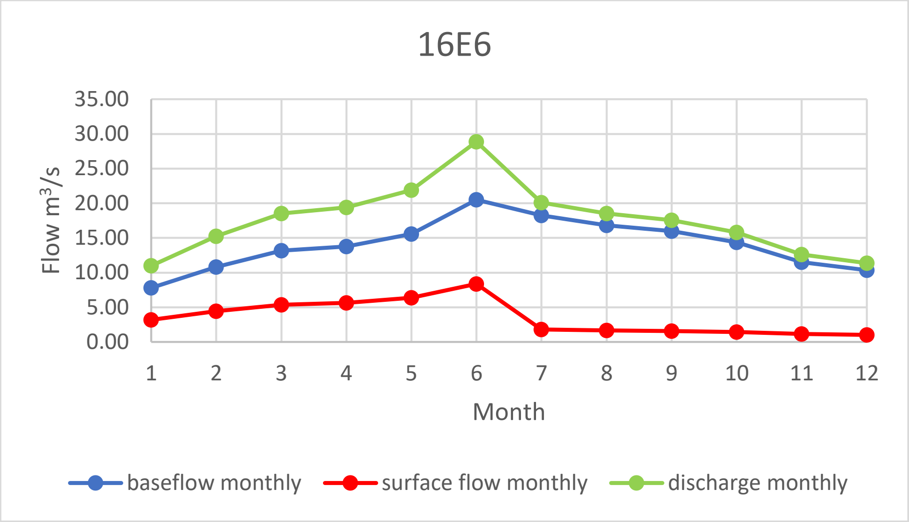

14A2
flow m³/s
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

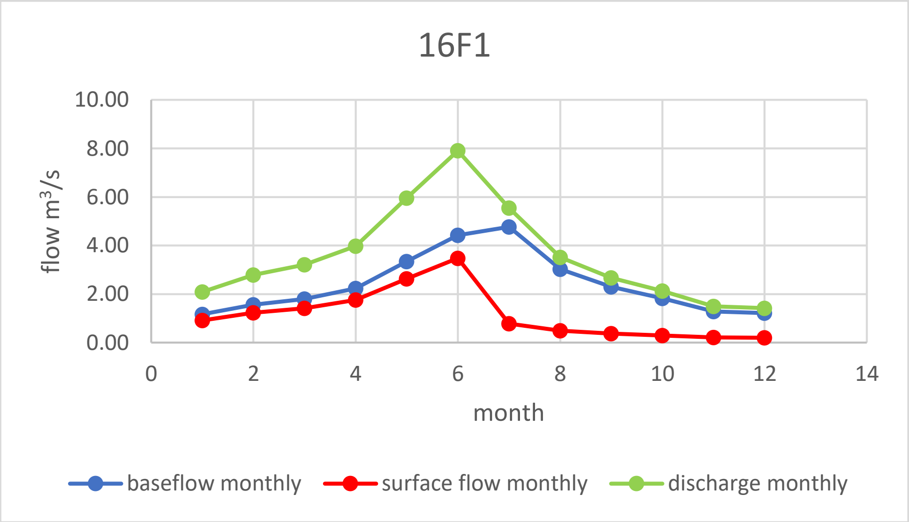

14C8
flow m³/s
25.00
20.00
15.00
10.00
5.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

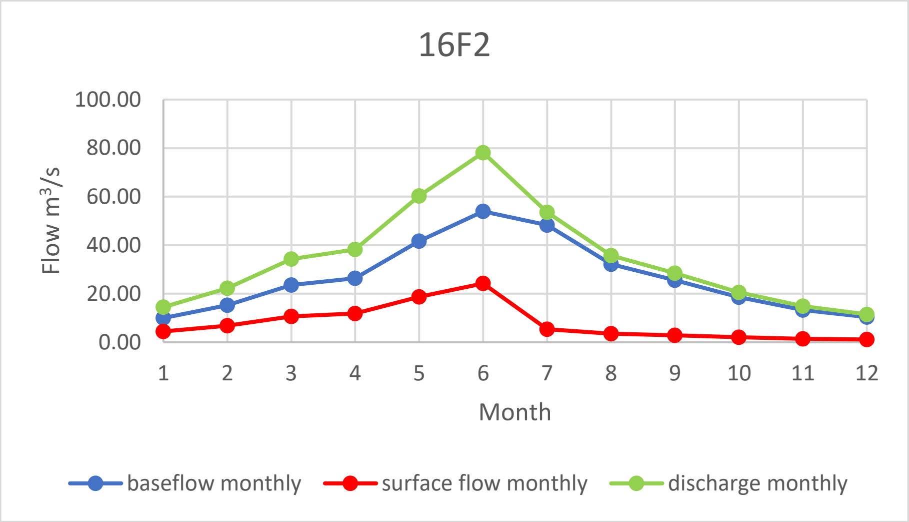

14D1
flow m³/s
400.00
300.00
200.00
100.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

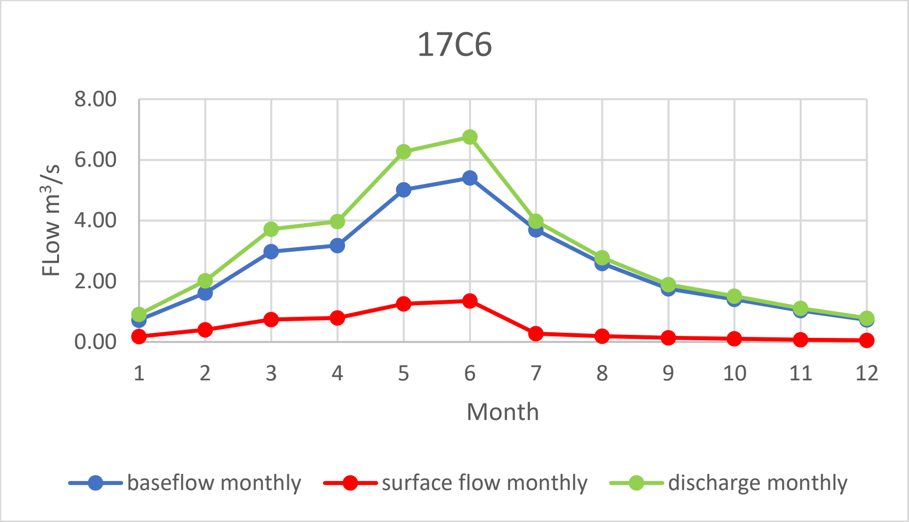

14C2
flow m³/s
15.00
10.00
5.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
month
baseflow monthly
surface flow monthly
discharge monthly

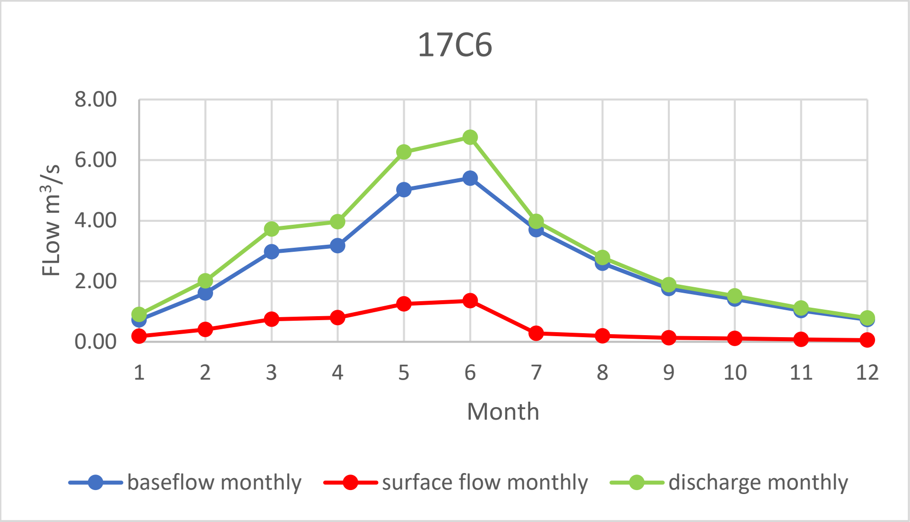

15A8
flow m³/s
25.00
20.00
15.00
10.00
5.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
Month
baseflow monthly
surface flow monthly
discharge monthly

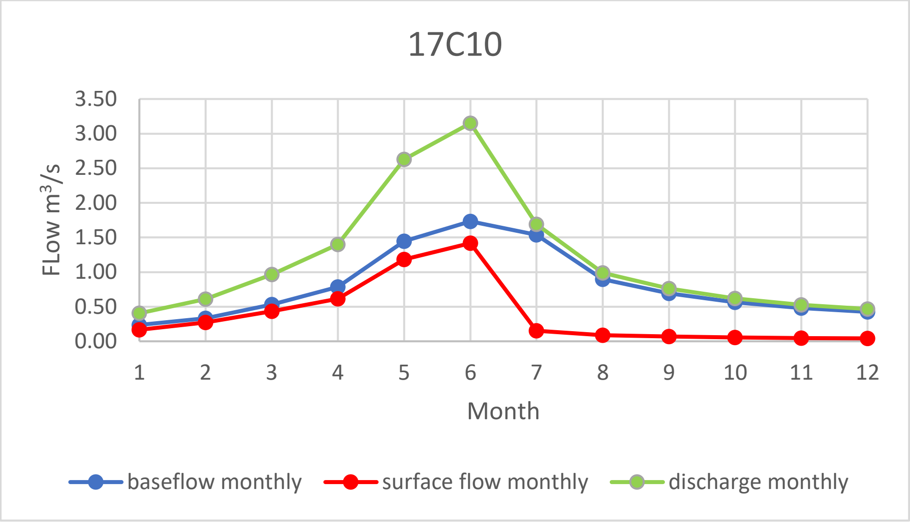

16E6
Flow m³/s
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
Month
baseflow monthly
surface flow monthly
discharge monthly


16F1
flow m³/s
10.00
8.00
6.00
4.00
2.00
0.00
0
2
4
6
8
10
12
14
month
baseflow monthly
surface flow monthly
discharge monthly


16F2
Flow m³/s
100.00
80.00
60.00
40.00
20.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
Month
baseflow monthly
surface flow monthly
discharge monthly

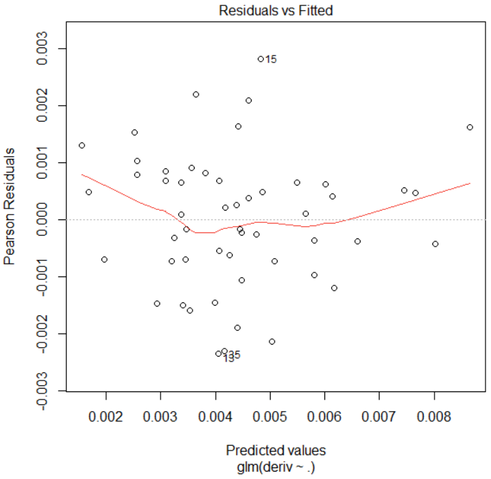

17C6
FLow m³/s
8.00
6.00
4.00
2.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
Month
baseflow monthly
surface flow monthly
discharge monthly

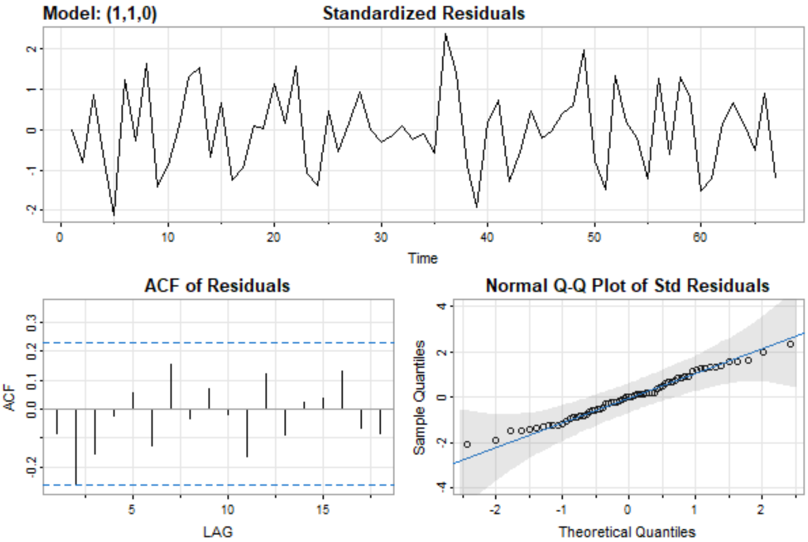

17C6
FLow m³/s
8.00
6.00
4.00
2.00
0.00
1
2
3
4
5
6
7
8
9
10
11
12
Month
baseflow monthly
surface flow monthly
discharge monthly


17C10
FLow m³/s
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1
2
3
4
5
6
7
8
9
10
11
12
Month
baseflow monthly
surface flow monthly
discharge monthly

Appendix E: Linear model results and assumptions for each month.

Month: January

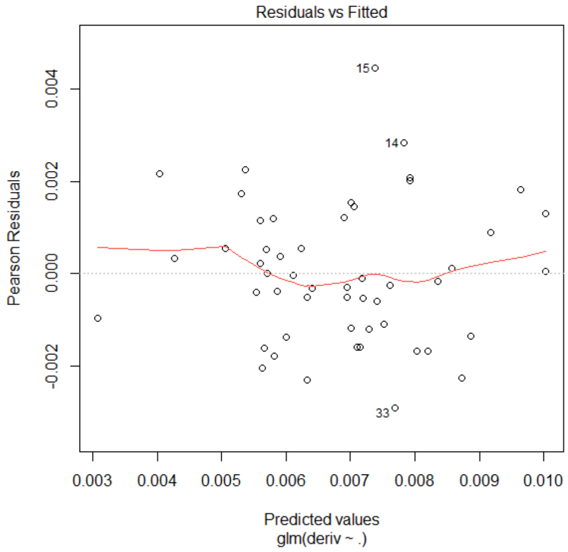


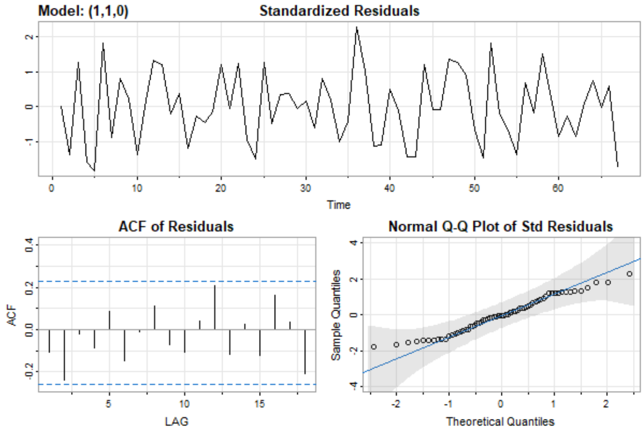


```
VIF
 av_3_month_precip      annual_precip  annual_precip_lag_1  annual_precip_lag_2  annual_precip_lag_3
          3.422354           2.874448             1.514986             1.297279             1.266748
annual_precip_lag_4  annual_precip_lag_5  annual_precip_lag_6  annual_precip_lag_7  annual_precip_lag_8
          1.317084           1.217314             1.271724             1.419319             1.355850
annual_precip_lag_9 annual_precip_lag_10 annual_precip_lag_11 annual_precip_lag_12 annual_precip_lag_13
          1.349283           1.398129             1.687821             1.549001             1.772584
annual_precip_lag_14 annual_precip_lag_15
```

```
3 months to January rate of lake level change

Coefficients:

                  Estimate Std. Error t value Pr(>|t|)

(Intercept)         -6.398e-03  5.587e-03  -1.145   0.2602

av_3_month_precip    1.006e-03  3.902e-04   2.579   0.0144 *

annual_precip        8.295e-04  8.052e-04   1.030   0.3102

annual_precip_lag_1   2.114e-04  5.821e-04   0.363   0.7187

annual_precip_lag_2   3.977e-04  5.339e-04   0.745   0.4615

annual_precip_lag_3   4.537e-05  5.104e-04   0.089   0.9297

annual_precip_lag_4   8.686e-04  5.221e-04   1.664   0.1054

annual_precip_lag_5  -5.035e-04  4.718e-04  -1.067   0.2934

annual_precip_lag_6   2.237e-04  4.706e-04   0.475   0.6375

annual_precip_lag_7  -2.676e-04  4.736e-04  -0.565   0.5758

annual_precip_lag_8   5.926e-05  4.669e-04   0.127   0.8997

annual_precip_lag_9   9.567e-04  4.626e-04   2.068   0.0463 *

annual_precip_lag_10 -1.118e-03  4.717e-04  -2.369   0.0236 *

annual_precip_lag_11  6.701e-05  4.937e-04   0.136   0.8928

annual_precip_lag_12  1.072e-03  4.735e-04   2.264   0.0300 *

annual_precip_lag_13 -9.922e-04  5.072e-04  -1.956   0.0587 .

annual_precip_lag_14  1.047e-04  5.245e-04   0.200   0.8429

annual_precip_lag_15 -8.307e-05  4.756e-04  -0.175   0.8624

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1


(Dispersion parameter for gaussian family taken to be 2.188724e-06)


    Null deviance: 1.8959e-04  on 51  degrees of freedom

Residual deviance: 7.4417e-05  on 34  degrees of freedom

AIC: -514.2
```

Month: February

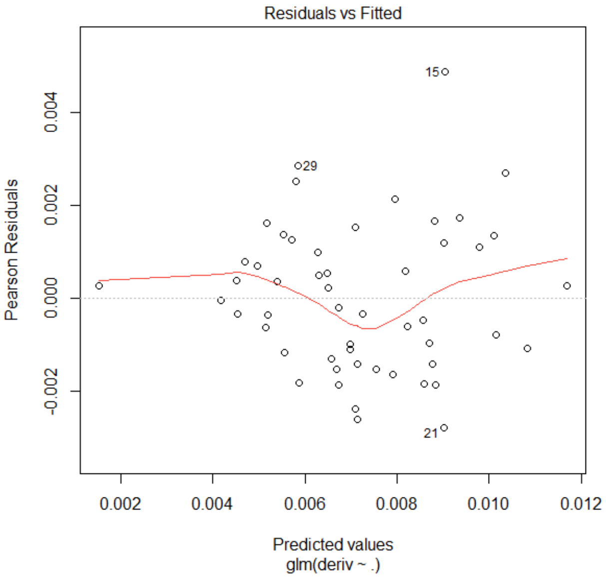


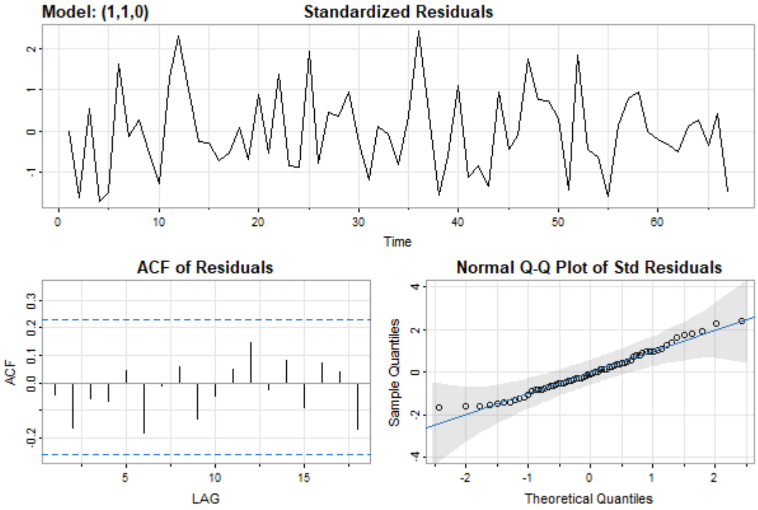


```
VIF
av_3_month_precip       annual_precip  annual_precip_lag_1  annual_precip_lag_2  annual_precip_lag_3
          2.920561           2.677872           1.255412           1.354781           1.445764
 annual_precip_lag_4  annual_precip_lag_5  annual_precip_lag_6  annual_precip_lag_7  annual_precip_lag_8
          1.640560           1.524375           1.549374           1.641872           1.730411
 annual_precip_lag_9 annual_precip_lag_10 annual_precip_lag_11 annual_precip_lag_12 annual_precip_lag_13
          1.674331           1.676409           2.360287           2.299583           2.016453
annual_precip_lag_14 annual_precip_lag_15
```

```
Call:
glm(formula = deriv ~ ., data = oct_3_month_deriv)


Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)         -2.940e-03  7.864e-03  -0.374   0.7108
av_3_month_precip    2.968e-04  4.198e-04   0.707   0.4844
annual_precip        2.154e-03  1.106e-03   1.947   0.0598 .
annual_precip_lag_1   5.848e-04  7.752e-04   0.754   0.4558
annual_precip_lag_2   4.842e-04  7.901e-04   0.613   0.5440
annual_precip_lag_3  -5.646e-04  7.837e-04  -0.720   0.4762
annual_precip_lag_4   2.477e-04  8.343e-04   0.297   0.7683
annual_precip_lag_5  -6.086e-05  7.647e-04  -0.080   0.9370
annual_precip_lag_6  -7.340e-04  7.228e-04  -1.015   0.3170
annual_precip_lag_7   2.982e-04  7.314e-04   0.408   0.6860
annual_precip_lag_8   2.086e-04  7.527e-04   0.277   0.7833
annual_precip_lag_9   6.427e-04  7.186e-04   0.894   0.3774
annual_precip_lag_10  2.138e-04  7.297e-04   0.293   0.7713
annual_precip_lag_11 -9.960e-04  8.334e-04  -1.195   0.2403
annual_precip_lag_12  1.088e-03  8.045e-04   1.352   0.1853
annual_precip_lag_13 -6.845e-04  7.541e-04  -0.908   0.3704
annual_precip_lag_14 -7.794e-05  7.129e-04  -0.109   0.9136
annual_precip_lag_15 -5.125e-05  6.556e-04  -0.078   0.9381
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Month: March

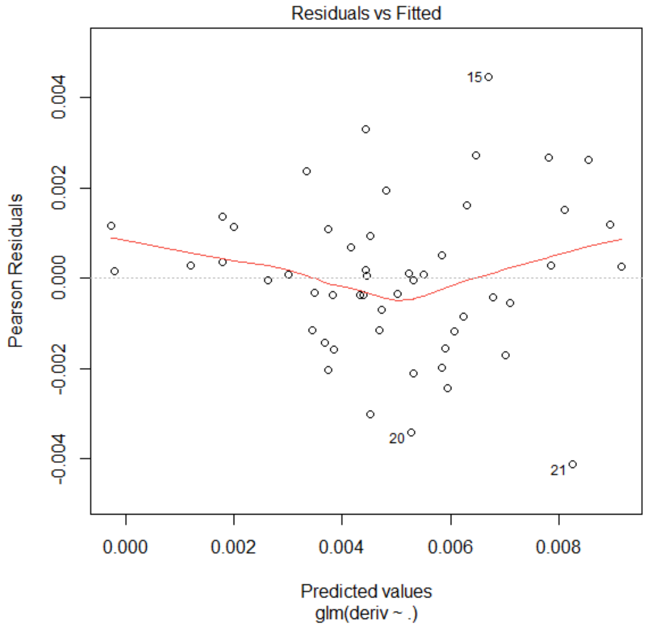

Residuals vs Fitted
Pearson Residuals
0.004
0.002
0.000
-0.002
15
29
21
0.002
0.004
0.006
0.008
0.010
0.012
Predicted values
glm(deriv ~ .)

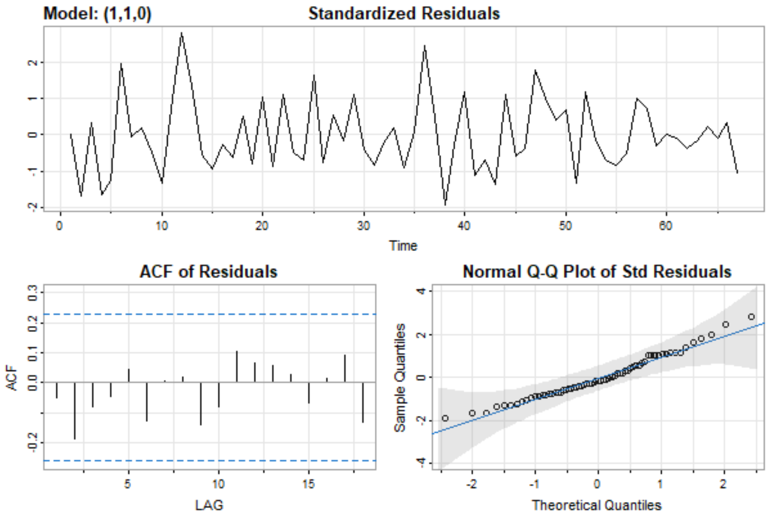

Model: (1,1,0)
Standardized Residuals
2
1
0
-1
0
10
20
30
40
50
60
Time
ACF of Residuals
ACF
0.3
0.2
0.1
0.0
-0.2
5
10
15
LAG
Normal Q-Q Plot of Std Residuals
Sample Quantiles
4
2
0
-2
-4
-2
-1
0
1
2
Theoretical Quantiles

```
VIF

av_3_month_precip       annual_precip  annual_precip_lag_1  annual_precip_lag_2  annual_precip_lag_3

         3.510832           2.964324           1.821258           1.921261           1.918577

 annual_precip_lag_4  annual_precip_lag_5  annual_precip_lag_6  annual_precip_lag_7  annual_precip_lag_8

         1.946267           1.883740           2.386054           2.224881           2.269582

 annual_precip_lag_9 annual_precip_lag_10 annual_precip_lag_11 annual_precip_lag_12 annual_precip_lag_13

         2.892924           2.497318           2.233852           2.480206           2.520550

annual_precip_lag_14 annual_precip_lag_15

         2.862036           1.948450
```

```
Call:

glm(formula = deriv ~ ., data = oct_3_month_deriv)



Coefficients:

                  Estimate Std. Error t value Pr(>|t|)

(Intercept)         -8.089e-03  7.869e-03  -1.028  0.31123

av_3_month_precip    1.245e-03  4.427e-04   2.813  0.00810 **

annual_precip        2.109e-03  1.303e-03   1.619  0.11473

annual_precip_lag_1  -9.614e-04  1.064e-03  -0.903  0.37280

annual_precip_lag_2   1.885e-03  1.065e-03   1.770  0.08577 .

annual_precip_lag_3  -1.189e-03  1.025e-03  -1.160  0.25414

annual_precip_lag_4  -9.499e-07  1.032e-03  -0.001  0.99927

annual_precip_lag_5   6.123e-04  9.974e-04   0.614  0.54334

annual_precip_lag_6  -4.331e-04  1.029e-03  -0.421  0.67634

annual_precip_lag_7   2.570e-04  9.620e-04   0.267  0.79095

annual_precip_lag_8   6.382e-05  9.674e-04   0.066  0.94779

annual_precip_lag_9   8.689e-04  1.071e-03   0.811  0.42299

annual_precip_lag_10 -5.385e-04  9.955e-04  -0.541  0.59206

annual_precip_lag_11 -1.131e-04  8.795e-04  -0.129  0.89842

annual_precip_lag_12 -3.480e-04  9.013e-04  -0.386  0.70178

annual_precip_lag_13  1.617e-03  9.172e-04   1.763  0.08686 .

annual_precip_lag_14 -2.664e-03  9.755e-04  -2.731  0.00993 **

annual_precip_lag_15  1.242e-03  8.031e-04   1.546  0.13134

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Month: April

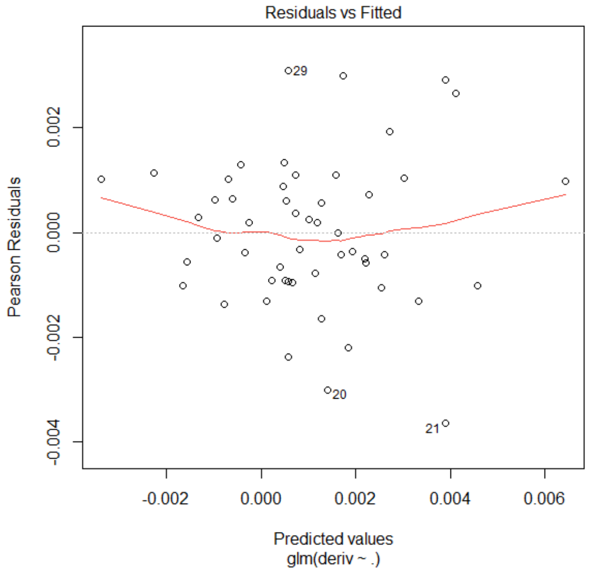

Residuals vs Fitted
Pearson Residuals
0.004
0.002
0.000
-0.002
-0.004
15
20
21
0.000
0.002
0.004
0.006
0.008
Predicted values
glm(deriv ~ .)

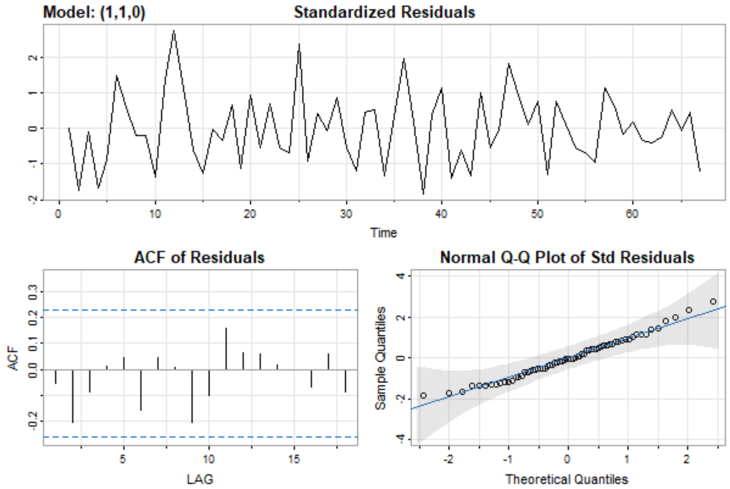

Model: (1,1,0)
Standardized Residuals
2
1
0
-1
-2
0
10
20
30
40
50
60
Time
ACF of Residuals
ACF
0.3
0.2
0.1
0.0
-0.2
5
10
15
LAG
Normal Q-Q Plot of Std Residuals
Sample Quantiles
4
2
0
-2
-4
-2
-1
0
1
2
Theoretical Quantiles

```
VIF

av_3_month_precip       annual_precip  annual_precip_lag_1  annual_precip_lag_2  annual_precip_lag_3

         3.758973            3.251136            1.555213            1.405912            1.615652

 annual_precip_lag_4  annual_precip_lag_5  annual_precip_lag_6  annual_precip_lag_7  annual_precip_lag_8

         1.531156            1.462434            1.706866            1.692813            1.708583

 annual_precip_lag_9 annual_precip_lag_10 annual_precip_lag_11 annual_precip_lag_12 annual_precip_lag_13

         1.980239            1.679523            1.754302            1.726033            1.760839

annual_precip_lag_14 annual_precip_lag_15

         1.519204            1.419515
```

```
Coefficients:

                  Estimate Std. Error t value Pr(>|t|)

(Intercept)         -6.312e-03  8.576e-03  -0.736   0.4668

av_3_month_precip    8.946e-04  4.912e-04   1.821   0.0774 .

annual_precip        2.782e-03  1.439e-03   1.934   0.0615 .

annual_precip_lag_1  -9.035e-05  1.027e-03  -0.088   0.9304

annual_precip_lag_2  -1.348e-04  9.659e-04  -0.140   0.8898

annual_precip_lag_3  -9.672e-04  9.852e-04  -0.982   0.3331

annual_precip_lag_4   1.462e-05  9.486e-04   0.015   0.9878

annual_precip_lag_5   7.842e-04  9.170e-04   0.855   0.3985

annual_precip_lag_6  -6.871e-04  9.029e-04  -0.761   0.4519

annual_precip_lag_7   3.544e-04  8.722e-04   0.406   0.6870

annual_precip_lag_8  -8.718e-05  8.720e-04  -0.100   0.9209

annual_precip_lag_9  -5.303e-04  9.210e-04  -0.576   0.5686

annual_precip_lag_10  5.336e-04  8.490e-04   0.628   0.5339

annual_precip_lag_11  5.258e-05  8.155e-04   0.064   0.9490

annual_precip_lag_12 -4.417e-04  7.868e-04  -0.561   0.5782

annual_precip_lag_13  1.249e-03  7.955e-04   1.570   0.1256

annual_precip_lag_14 -2.782e-04  7.341e-04  -0.379   0.7071

annual_precip_lag_15 -1.779e-04  7.073e-04  -0.251   0.8030

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Month: May

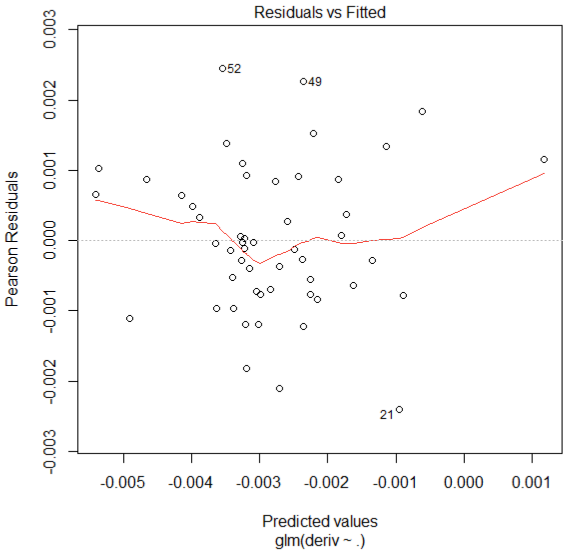

Residuals vs Fitted
29
20
21
Pearson Residuals
0.002
0.000
-0.002
-0.004
-0.002
0.000
0.002
0.004
0.006
Predicted values
glm(deriv ~ .)

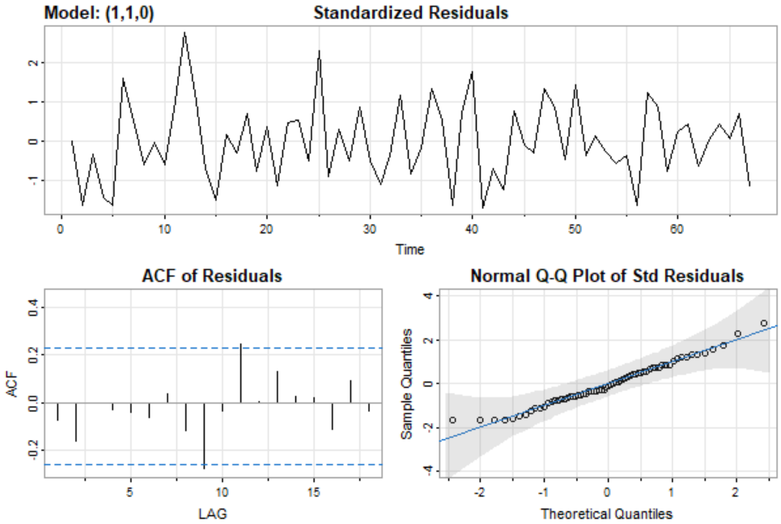

Model: (1,1,0)
Standardized Residuals
2
1
0
-1
-2
0
10
20
30
40
50
60
Time
ACF of Residuals
ACF
0.3
0.2
0.1
0.0
-0.2
5
10
15
LAG
Normal Q-Q Plot of Std Residuals
Sample Quantiles
4
2
0
-2
-4
-2
-1
0
1
2
Theoretical Quantiles

```
VIF

 av_3_month_precip       annual_precip  annual_precip_lag_1  annual_precip_lag_2  annual_precip_lag_3

          2.512103            2.441564            1.350552            1.381527            1.524936

 annual_precip_lag_4  annual_precip_lag_5  annual_precip_lag_6  annual_precip_lag_7  annual_precip_lag_8

          1.449997            1.349240            1.543553            1.594412            1.742659

 annual_precip_lag_9 annual_precip_lag_10 annual_precip_lag_11 annual_precip_lag_12 annual_precip_lag_13

          1.696727            1.609220            1.612863            1.664732            1.696006

annual_precip_lag_14 annual_precip_lag_15
```

```
                      Estimate Std. Error t value Pr(>|t|)

(Intercept)          -4.013e-03  7.216e-03  -0.556   0.5818

av_3_month_precip     9.428e-04  4.163e-04   2.265   0.0300 *

annual_precip         2.174e-03  1.015e-03   2.141   0.0395 *

annual_precip_lag_1  -4.856e-04  7.784e-04  -0.624   0.5369

annual_precip_lag_2  -1.057e-03  7.819e-04  -1.352   0.1852

annual_precip_lag_3  -3.049e-04  7.798e-04  -0.391   0.6983

annual_precip_lag_4  -7.930e-05  7.516e-04  -0.106   0.9166

annual_precip_lag_5   5.118e-04  7.183e-04   0.712   0.4810

annual_precip_lag_6  -2.825e-04  7.046e-04  -0.401   0.6909

annual_precip_lag_7   8.148e-05  6.941e-04   0.117   0.9072

annual_precip_lag_8  -3.772e-04  7.198e-04  -0.524   0.6037

annual_precip_lag_9  -6.392e-04  7.017e-04  -0.911   0.3687

annual_precip_lag_10 -4.945e-07  6.839e-04  -0.001   0.9994

annual_precip_lag_11  3.410e-04  6.452e-04   0.528   0.6006

annual_precip_lag_12  1.160e-04  6.377e-04   0.182   0.8568

annual_precip_lag_13  1.266e-03  6.442e-04   1.966   0.0575 .

annual_precip_lag_14 -1.862e-04  6.046e-04  -0.308   0.7600

annual_precip_lag_15 -2.719e-04  5.776e-04  -0.471   0.6409

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Month: June

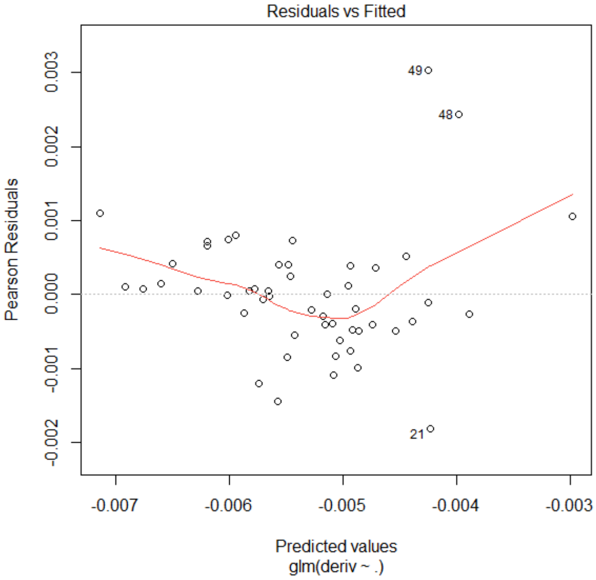


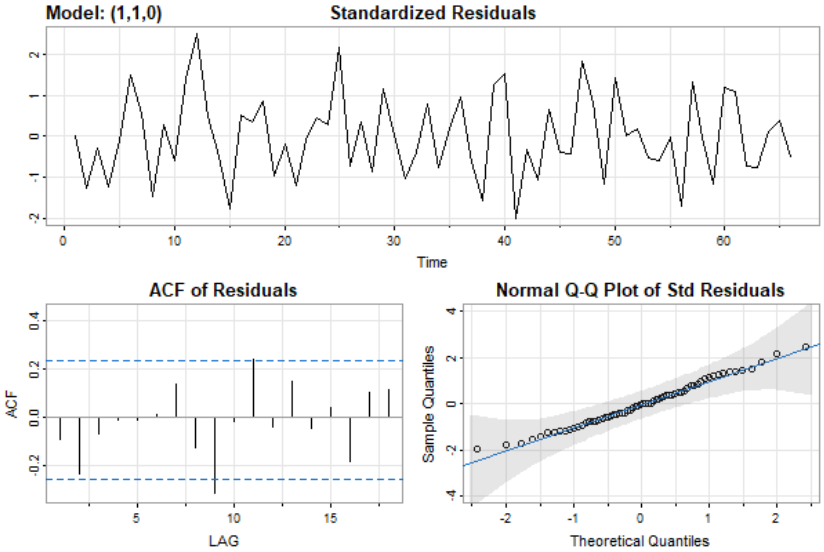


```
VIF
 av_3_month_precip       annual_precip  annual_precip_lag_1  annual_precip_lag_2  annual_precip_lag_3
         1.521943          1.577020          1.354984          1.395585          1.466297
annual_precip_lag_4  annual_precip_lag_5  annual_precip_lag_6  annual_precip_lag_7  annual_precip_lag_8
         1.440670          1.326491          1.513514          1.560660          1.575897
annual_precip_lag_9 annual_precip_lag_10 annual_precip_lag_11 annual_precip_lag_12 annual_precip_lag_13
         1.694286          1.624712          1.701254          1.656418          1.581872
annual_precip_lag_14 annual_precip_lag_15
         1.466824          1.361640
```

```
Coefficients:

                  Estimate Std. Error t value Pr(>|t|)

(Intercept)         -5.214e-03  5.179e-03  -1.007   0.3212

av_3_month_precip    1.122e-03  4.857e-04   2.311   0.0270 *

annual_precip        1.313e-03  5.927e-04   2.216   0.0335 *

annual_precip_lag_1  -9.328e-04  5.659e-04  -1.648   0.1085

annual_precip_lag_2  -1.386e-03  5.702e-04  -2.431   0.0205 *

annual_precip_lag_3   2.332e-04  5.594e-04   0.417   0.6794

annual_precip_lag_4  -3.023e-05  5.459e-04  -0.055   0.9562

annual_precip_lag_5   4.904e-04  5.174e-04   0.948   0.3499

annual_precip_lag_6   1.418e-04  5.110e-04   0.277   0.7831

annual_precip_lag_7  -9.103e-05  5.026e-04  -0.181   0.8573

annual_precip_lag_8  -7.643e-04  5.007e-04  -1.527   0.1361

annual_precip_lag_9  -3.354e-04  5.131e-04  -0.654   0.5177

annual_precip_lag_10  1.562e-04  5.029e-04   0.311   0.7581

annual_precip_lag_11  3.041e-04  4.840e-04   0.628   0.5341

annual_precip_lag_12  3.096e-04  4.642e-04   0.667   0.5093

annual_precip_lag_13  1.064e-03  4.540e-04   2.343   0.0251 *

annual_precip_lag_14 -4.874e-05  4.343e-04  -0.112   0.9113

annual_precip_lag_15 -1.466e-05  4.174e-04  -0.035   0.9722

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Month: July

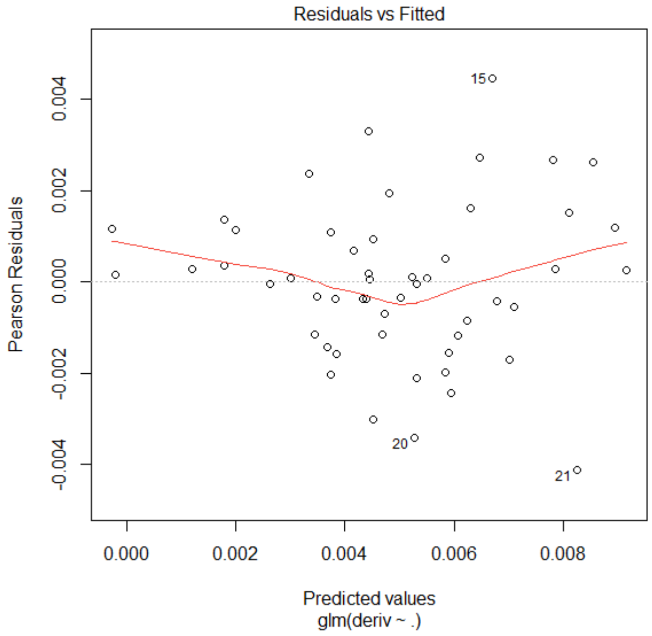


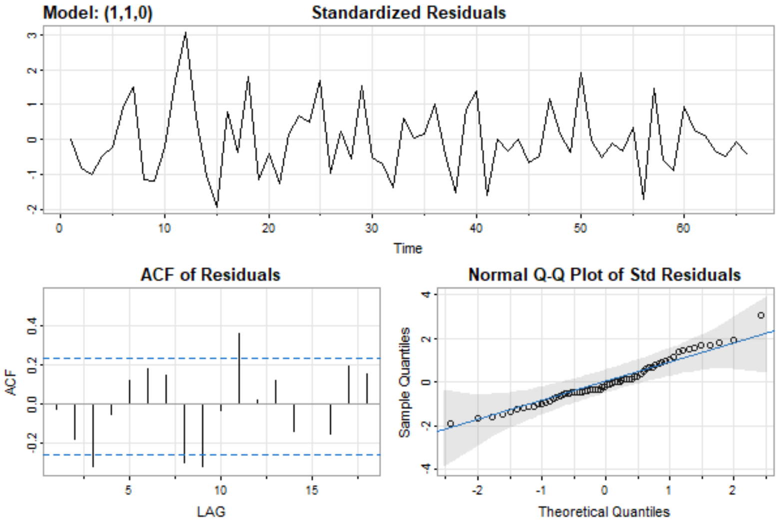


```
VIF
av_3_month_precip       annual_precip  annual_precip_lag_1  annual_precip_lag_2  annual_precip_lag_3
         1.605540          1.463175          1.426014          1.399730          1.525440
 annual_precip_lag_4  annual_precip_lag_5  annual_precip_lag_6  annual_precip_lag_7  annual_precip_lag_8
         1.432124          1.359501          1.467260          1.507034          1.567578
 annual_precip_lag_9 annual_precip_lag_10 annual_precip_lag_11 annual_precip_lag_12 annual_precip_lag_13
         1.645382          1.530293          1.631739          1.648023          1.576469
annual_precip_lag_14 annual_precip_lag_15
         1.406404          1.411123
```

```
Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)         -1.874e-03  4.187e-03  -0.448  0.65729
av_3_month_precip    -4.099e-04  8.507e-04  -0.482  0.63309
annual_precip        6.230e-04  4.664e-04   1.336  0.19070
annual_precip_lag_1  -1.422e-03  4.606e-04  -3.088  0.00407 **
annual_precip_lag_2  -1.134e-03  4.545e-04  -2.496  0.01774 *
annual_precip_lag_3   6.474e-04  4.559e-04   1.420  0.16498
annual_precip_lag_4  -8.263e-05  4.349e-04  -0.190  0.85048
annual_precip_lag_5   3.765e-04  4.199e-04   0.897  0.37644
annual_precip_lag_6   2.886e-04  4.016e-04   0.719  0.47746
annual_precip_lag_7  -6.086e-04  3.947e-04  -1.542  0.13260
annual_precip_lag_8  -6.365e-04  3.990e-04  -1.595  0.12021
annual_precip_lag_9  -1.821e-04  4.050e-04  -0.450  0.65590
annual_precip_lag_10 -2.132e-04  3.902e-04  -0.546  0.58850
annual_precip_lag_11  6.001e-04  3.801e-04   1.579  0.12396
annual_precip_lag_12  5.092e-04  3.706e-04   1.374  0.17872
annual_precip_lag_13  5.357e-04  3.628e-04   1.477  0.14926
annual_precip_lag_14 -1.613e-04  3.413e-04  -0.473  0.63965
annual_precip_lag_15 -3.007e-04  3.476e-04  -0.865  0.39320
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for gaussian family taken to be 1.049919e-06)

    Null deviance: 6.8254e-05  on 50  degrees of freedom
Residual deviance: 3.4647e-05  on 33  degrees of freedom
AIC: -541.58
```

Month: August

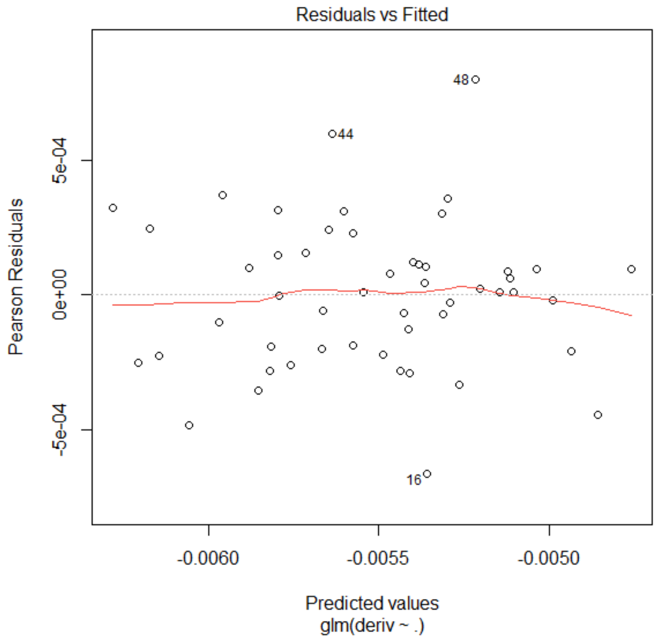


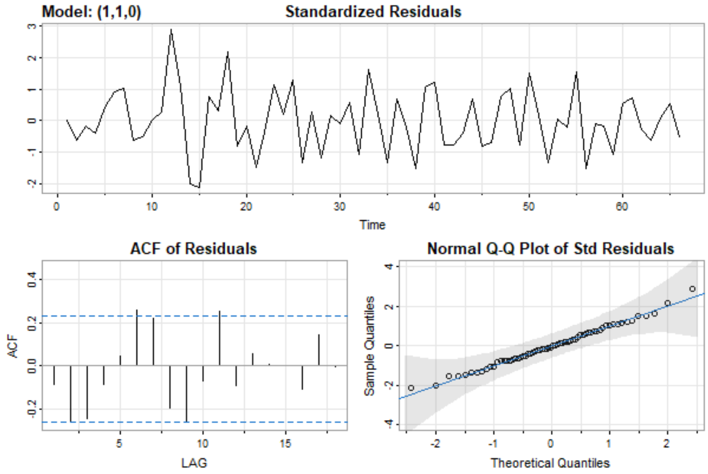


```
VIF

av_3_month_precip       annual_precip  annual_precip_lag_1  annual_precip_lag_2  annual_precip_lag_3

          1.662750           1.361589            1.315259            1.398276            1.415998

 annual_precip_lag_4  annual_precip_lag_5  annual_precip_lag_6  annual_precip_lag_7  annual_precip_lag_8

          1.422683           1.291910            1.442821            1.493376            1.644404

 annual_precip_lag_9 annual_precip_lag_10 annual_precip_lag_11 annual_precip_lag_12 annual_precip_lag_13

          1.597228           1.691778            1.615228            1.640050            1.669851

annual_precip_lag_14 annual_precip_lag_15

          1.405074           1.352534
```

```
Coefficients:

                    Estimate Std. Error t value Pr(>|t|)

(Intercept)          2.362e-03  3.308e-03   0.714   0.4803

av_3_month_precip    -2.309e-03  1.370e-03  -1.686   0.1013

annual_precip        -2.893e-05  3.394e-04  -0.085   0.9326

annual_precip_lag_1  -8.854e-04  3.337e-04  -2.653   0.0122 *

annual_precip_lag_2  -6.616e-04  3.430e-04  -1.929   0.0623 .

annual_precip_lag_3   2.342e-04  3.329e-04   0.703   0.4867

annual_precip_lag_4  -3.227e-04  3.274e-04  -0.986   0.3315

annual_precip_lag_5   4.182e-05  3.093e-04   0.135   0.8933

annual_precip_lag_6   3.884e-05  3.010e-04   0.129   0.8981

annual_precip_lag_7  -6.589e-04  2.971e-04  -2.217   0.0336 *

annual_precip_lag_8  -5.005e-04  3.091e-04  -1.619   0.1149

annual_precip_lag_9  -7.451e-05  3.018e-04  -0.247   0.8065

annual_precip_lag_10 -4.140e-04  3.103e-04  -1.334   0.1914

annual_precip_lag_11  4.383e-04  2.863e-04   1.531   0.1353

annual_precip_lag_12  2.002e-04  2.799e-04   0.715   0.4795

annual_precip_lag_13  6.361e-05  2.826e-04   0.225   0.8233

annual_precip_lag_14  2.360e-05  2.583e-04   0.091   0.9278

annual_precip_lag_15 -2.794e-04  2.578e-04  -1.084   0.2861

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1


(Dispersion parameter for gaussian family taken to be 6.04093e-07)
```

Month: September

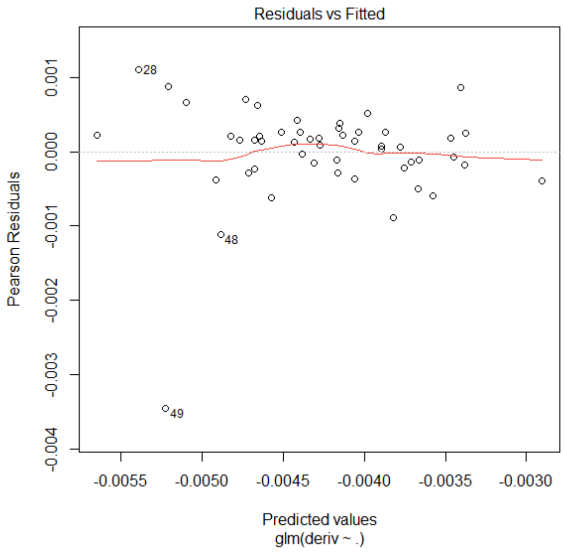


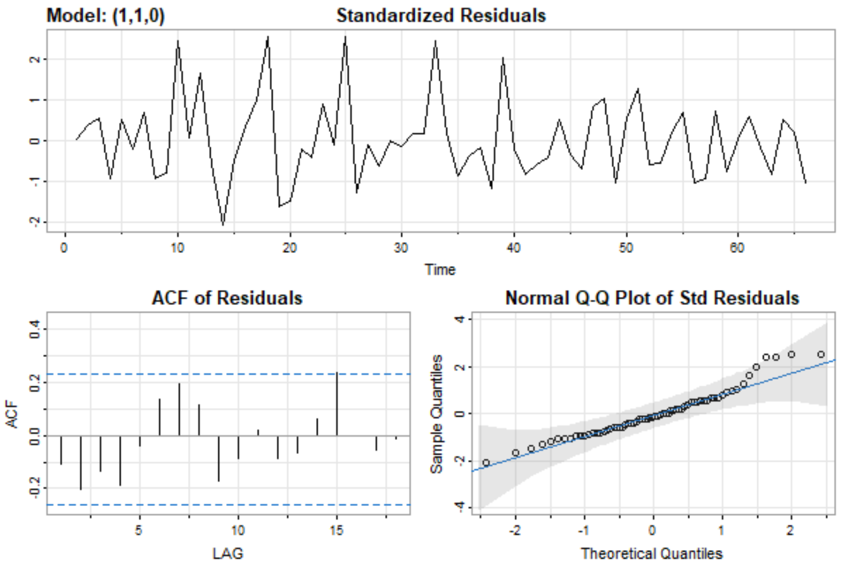


```
VIF

av_3_month_precip       annual_precip  annual_precip_lag_1  annual_precip_lag_2  annual_precip_lag_3

         1.737403            1.463214            1.325147            1.411883            1.387674

 annual_precip_lag_4  annual_precip_lag_5  annual_precip_lag_6  annual_precip_lag_7  annual_precip_lag_8

         1.417555            1.276342            1.503166            1.633940            1.517079

 annual_precip_lag_9 annual_precip_lag_10 annual_precip_lag_11 annual_precip_lag_12 annual_precip_lag_13

         1.551316            1.685149            1.505230            1.655519            1.648587

annual_precip_lag_14 annual_precip_lag_15

         1.397824            1.347285
```

```
Coefficients:

                     Estimate Std. Error t value Pr(>|t|)

(Intercept)          2.429e-03  1.451e-03   1.673  0.10369

av_3_month_precip    -7.722e-04  6.105e-04  -1.265  0.21474

annual_precip        -1.071e-04  1.513e-04  -0.708  0.48394

annual_precip_lag_1  -1.738e-04  1.440e-04  -1.207  0.23616

annual_precip_lag_2  -1.527e-04  1.483e-04  -1.030  0.31054

annual_precip_lag_3   9.793e-06  1.420e-04   0.069  0.94545

annual_precip_lag_4  -4.766e-04  1.408e-04  -3.386  0.00185 **

annual_precip_lag_5  -3.340e-04  1.322e-04  -2.527  0.01647 *

annual_precip_lag_6  -2.002e-04  1.326e-04  -1.510  0.14051

annual_precip_lag_7  -4.465e-04  1.343e-04  -3.324  0.00218 **

annual_precip_lag_8  -1.817e-04  1.283e-04  -1.416  0.16601

annual_precip_lag_9  -3.667e-05  1.286e-04  -0.285  0.77721

annual_precip_lag_10 -3.007e-04  1.336e-04  -2.251  0.03117 *

annual_precip_lag_11  1.730e-04  1.203e-04   1.438  0.15988

annual_precip_lag_12 -2.396e-04  1.224e-04  -1.957  0.05880 .

annual_precip_lag_13  2.762e-05  1.223e-04   0.226  0.82265

annual_precip_lag_14 -2.811e-04  1.122e-04  -2.505  0.01736 *

annual_precip_lag_15 -4.885e-05  1.121e-04  -0.436  0.66588

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Month: October

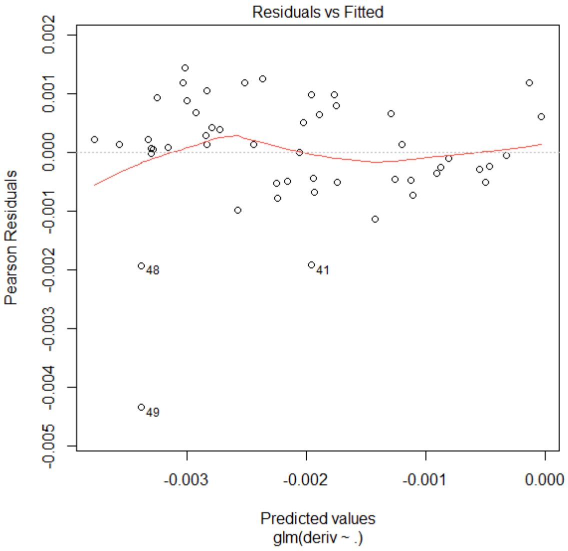


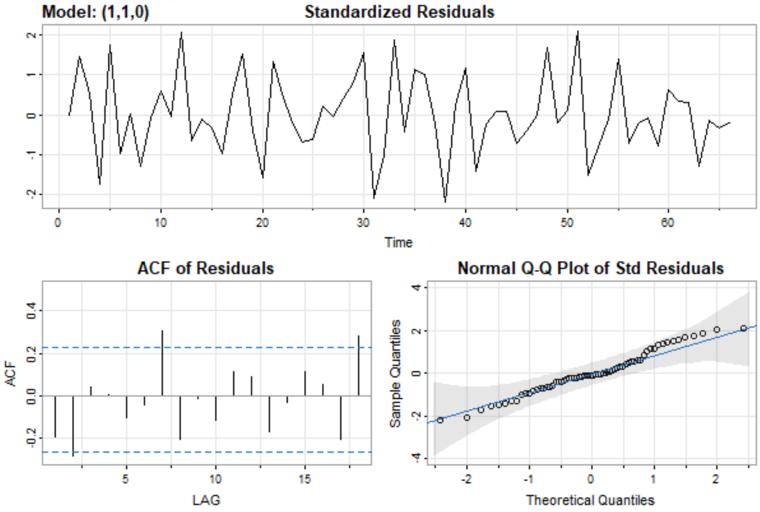


```
VIF
 av_3_month_precip      annual_precip  annual_precip_lag_1  annual_precip_lag_2  annual_precip_lag_3
          1.833678          1.718542          1.314096          1.400054          1.421470
 annual_precip_lag_4  annual_precip_lag_5  annual_precip_lag_6  annual_precip_lag_7  annual_precip_lag_8
          1.418967          1.255093          1.611194          1.441622          1.468234
 annual_precip_lag_9 annual_precip_lag_10 annual_precip_lag_11 annual_precip_lag_12 annual_precip_lag_13
          1.562832          1.485739          1.496388          1.587063          1.585045
annual_precip_lag_14 annual_precip_lag_15
          1.397292          1.731367
```

```
Coefficients:

                 Estimate Std. Error t value Pr(>|t|)

(Intercept)         2.558e-03  3.421e-03   0.748   0.4599

av_3_month_precip    1.668e-03  1.208e-03   1.381   0.1766

annual_precip        2.113e-05  3.854e-04   0.055   0.9566

annual_precip_lag_1   5.166e-04  3.372e-04   1.532   0.1351

annual_precip_lag_2  -1.881e-04  3.470e-04  -0.542   0.5914

annual_precip_lag_3  -5.073e-05  3.385e-04  -0.150   0.8818

annual_precip_lag_4  -3.636e-04  3.317e-04  -1.096   0.2810

annual_precip_lag_5  -5.382e-04  3.067e-04  -1.755   0.0886 .

annual_precip_lag_6  -4.550e-04  3.255e-04  -1.398   0.1714

annual_precip_lag_7   2.840e-05  2.991e-04   0.095   0.9249

annual_precip_lag_8  -7.788e-05  2.992e-04  -0.260   0.7962

annual_precip_lag_9  -8.031e-05  3.054e-04  -0.263   0.7942

annual_precip_lag_10 -1.679e-04  2.973e-04  -0.565   0.5760

annual_precip_lag_11 -2.586e-05  2.848e-04  -0.091   0.9282

annual_precip_lag_12 -5.931e-04  2.829e-04  -2.097   0.0438 *

annual_precip_lag_13 -1.109e-05  2.829e-04  -0.039   0.9690

annual_precip_lag_14 -6.994e-04  2.651e-04  -2.639   0.0126 *

annual_precip_lag_15  8.524e-05  2.991e-04   0.285   0.7775

---

Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1


(Dispersion parameter for gaussian family taken to be 6.446799e-07)
```

Month: November





```
VIF

av_3_month_precip      annual_precip  annual_precip_lag_1  annual_precip_lag_2  annual_precip_lag_3

        2.213513         1.996956          1.543676          1.416230          1.581193

 annual_precip_lag_4  annual_precip_lag_5  annual_precip_lag_6  annual_precip_lag_7  annual_precip_lag_8

        1.427853         1.363549          1.497215          1.572132          1.514049

 annual_precip_lag_9 annual_precip_lag_10 annual_precip_lag_11 annual_precip_lag_12 annual_precip_lag_13

        1.628846         1.584565          1.646902          1.650618          1.714944

annual_precip_lag_14 annual_precip_lag_15

        1.570255         1.643335
```

```
Coefficients:

                    Estimate Std. Error t value Pr(>|t|)

(Intercept)          4.104e-03  5.123e-03   0.801   0.4288

av_3_month_precip    1.295e-03  6.220e-04   2.081   0.0452 *

annual_precip        1.956e-04  5.979e-04   0.327   0.7457

annual_precip_lag_1   6.891e-04  5.252e-04   1.312   0.1986

annual_precip_lag_2  -4.954e-04  4.996e-04  -0.992   0.3286

annual_precip_lag_3   1.614e-04  5.148e-04   0.313   0.7559

annual_precip_lag_4  -2.738e-04  4.798e-04  -0.571   0.5721

annual_precip_lag_5  -8.658e-04  4.642e-04  -1.865   0.0711 .

annual_precip_lag_6  -1.112e-04  4.480e-04  -0.248   0.8056

annual_precip_lag_7   6.344e-05  4.514e-04   0.141   0.8891

annual_precip_lag_8  -2.095e-04  4.334e-04  -0.483   0.6320

annual_precip_lag_9  -1.622e-05  4.481e-04  -0.036   0.9713

annual_precip_lag_10 -6.162e-04  4.382e-04  -1.406   0.1690

annual_precip_lag_11 -1.492e-04  4.394e-04  -0.340   0.7363

annual_precip_lag_12 -2.858e-04  4.210e-04  -0.679   0.5019

annual_precip_lag_13 -4.581e-05  4.293e-04  -0.107   0.9157

annual_precip_lag_14 -1.070e-03  4.122e-04  -2.597   0.0139 *

annual_precip_lag_15  3.243e-04  4.222e-04   0.768   0.4479

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Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1


(Dispersion parameter for gaussian family taken to be 1.449588e-06)
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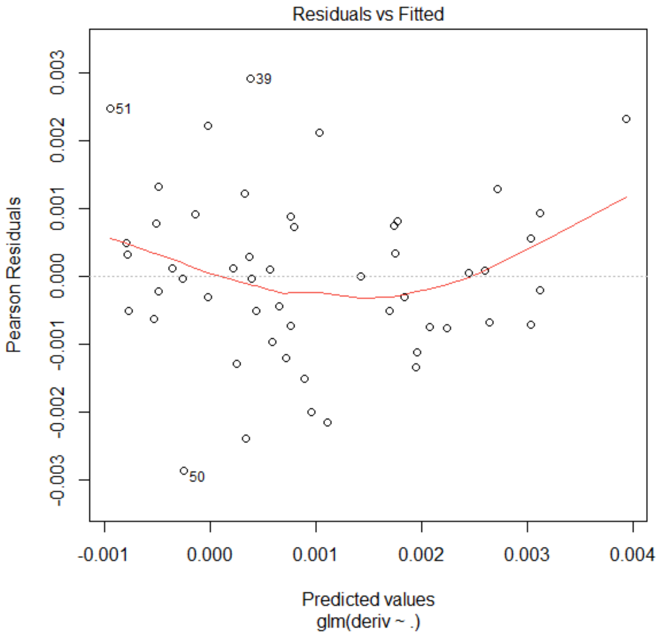
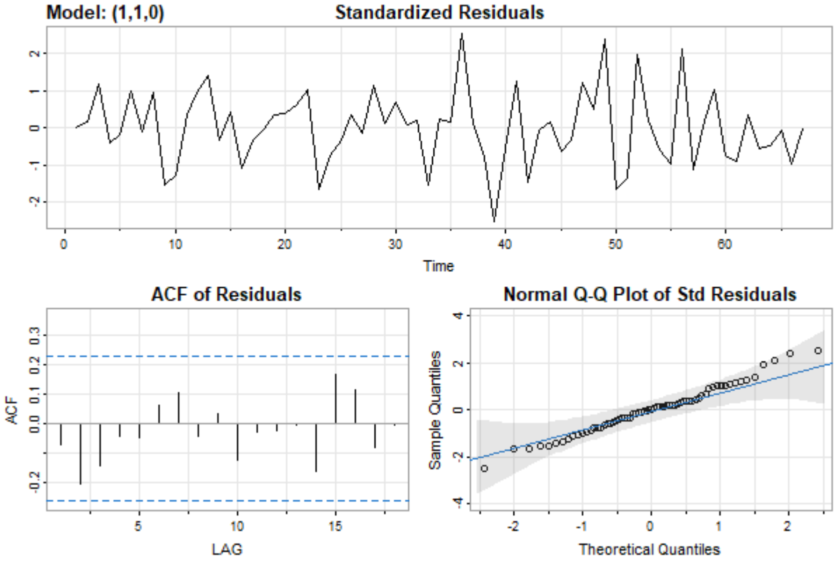
Month: December





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VIF

av_3_month_precip       annual_precip  annual_precip_lag_1  annual_precip_lag_2  annual_precip_lag_3

         3.557008           2.873030           1.785145           1.417491           1.479044

 annual_precip_lag_4  annual_precip_lag_5  annual_precip_lag_6  annual_precip_lag_7
annual_precip_lag_8

         1.420462           1.503738           1.478193           1.440459           1.407695

 annual_precip_lag_9 annual_precip_lag_10 annual_precip_lag_11 annual_precip_lag_12
annual_precip_lag_13

         1.580903           1.399276           1.757517           1.698474           1.764657

annual_precip_lag_14 annual_precip_lag_15

         1.972504           1.776494
```

```
Call:
glm(formula = deriv ~ ., data = oct_3_month_deriv)


Coefficients:
                    Estimate Std. Error t value Pr(>|t|)
(Intercept)         -0.0030565  0.0056627  -0.540    0.593
av_3_month_precip    0.0007772  0.0004944   1.572    0.125
annual_precip        0.0008555  0.0008274   1.034    0.308
annual_precip_lag_1  0.0005847  0.0006443   0.907    0.371
annual_precip_lag_2 -0.0004169  0.0005657  -0.737    0.466
annual_precip_lag_3  0.0002562  0.0005630   0.455    0.652
annual_precip_lag_4  0.0001566  0.0005503   0.285    0.778
annual_precip_lag_5 -0.0003404  0.0005405  -0.630    0.533
annual_precip_lag_6  0.0001205  0.0005189   0.232    0.818
annual_precip_lag_7 -0.0001662  0.0004982  -0.333    0.741
annual_precip_lag_8  0.0004399  0.0004919   0.894    0.378
annual_precip_lag_9  0.0000504  0.0005219   0.097    0.924
annual_precip_lag_10 -0.0006648  0.0004755  -1.398    0.171
annual_precip_lag_11  0.0001145  0.0005299   0.216    0.830
annual_precip_lag_12  0.0003003  0.0005230   0.574    0.570
annual_precip_lag_13 -0.0007053  0.0005324  -1.325    0.194
annual_precip_lag_14 -0.0004515  0.0005604  -0.806    0.426
annual_precip_lag_15  0.0004358  0.0004987   0.874    0.388


(Dispersion parameter for gaussian family taken to be 2.253866e-06)
```

4.2.1 Postface

This piece directly responded to RQ1 by achieving SO1 and exploring how groundwater interacts with surface water in Malawi, taking the example of Lake Malawi. The significance of groundwater for Lake Malawi's water storage evidenced in this paper make inclusion of groundwater essential in any considerations of current and future water security within Malawi. Despite the significance of groundwater to surface water storage, most models and conceptualisations of Malawi's water resources fail to incorporate groundwater (Bhave et al., 2019; Calder et al., 1995; Drayton et al., 1984; Neuland et al., 1984). In models of Malawi's water resources where groundwater has been considered, they are limited to water balance approaches which unable to provide detailed representations of surface and groundwater interactions (Kumambala et al., 2010; Shela et al., 2000; Lyons et al., 2011).

To ensure future water security for Malawi, conceptualisation of Malawi's water resources emphasising groundwater dynaMICS, is essential. Informed water policy decisions will require a better understanding of groundwater availability to ensure holistic water security. This need is directly addressed within the next portion of this chapter, expanding on the increased understanding of the interplay between Malawi's groundwater and surface water resources to develop a holistic understanding of Malawi's water security. The quantification of trends in Malawi's groundwater storage provides vital information to guide current and future water policy.

4.3 Stakeholder informed approach improves national modelling of water resources for a Sub-Saharan African Basin

Rebekah Hinton[1,2], Dor Fridman[3], Mikhail Smilovic[3], Barbara Willarts[3], Limbikani Banda[1,4], Kit Macleod[2], Mads Troldborg[2], Robert Kalin[1]

[1] Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow G1 1XJ, UK
[2] The James Hutton Institute, Craigiebuckler, Aberdeen AB15 8QH, UK
[3] International Institute of Applied Systems Analysis (IIASA), Schlossplatz 1, Laxenburg, Austria
[4] Department of Water Resources, Ministry of Water and Sanitation, Government of Malawi, Private Bag 390, Lilongwe, Malawi

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Abstract

We apply a global hydrological model, the Community Water Model (CWatM), to Malawi. To effectively represent Malawi's water resources, we couple a high-resolution version of CwatM (5 arc minute resolution) with MODFLOW (5km resolution), enabling a high-resolution, national surface and groundwater model. Semi-structured stakeholder interviews were conducted to accurately represent Malawi's water governance, identifying key adjustments that reflect national water resources. Model modifications were implemented based on stakeholder engagement. Notably, we implement modifications to account for small-holder agriculture and 'dambo' wetlands. National characteristics of water and sanitation were also included; the model was developed to include pit-latrine sanitation, used by over 90% of the population. Spatial variation within domestic water use, both source and quantity, between urban and rural areas was also incorporated. Such model modifications significantly improved model performance, we suggest similar developments should be considered in modelling national water resources in other Southern-African countries.

Basin-wide scale model validation was undertaken by comparison with remote sensing observations of evapotranspiration, precipitation, and changes in total water storage (using GRACE Satellite data). Model calibration was undertaken by comparison to river discharge data at 35 national discharge stations.

We model that 652km^3 of available groundwater was stored within aquifer units in Malawi by the end of 2009 (the currently available estimate of groundwater storage in Malawi is between 96.7 and 1,108 km^3). Our

model shows a consistent decline in groundwater levels since 1980 (the beginning of our study period). In total, we estimate a decline of 17.8km^3 in groundwater storage in Malawi from 1980-2009, raising significant concerns for future water security in the country. Not only does this model provide unprecedented insight into Malawi's water security, particularly regarding the unseen but critical groundwater resource, further model development will enable forecasting of future water security issues under climate and socio-economic change.

1. Introduction

As Africa's third largest lake, and the fifth largest lake by volume in the world (Herdendorf, 1984), Lake Malawi (or Lake Nyasa) dominates Malawi's water resources, both in perception and practice. Yet, despite surface water's dominance, groundwater is arguably the country's the most pivotal source of water, providing over 80% of domestic needs (Graham and Polizzotto, 2013). Within domestic water dynaMICS, rural communities are typically more reliant on groundwater; it is estimated that 82% of the rural population and 20% of the urban population depend on groundwater to meet their water needs (Chavula, 2012). This makes rural communities particularly vulnerable to reduced groundwater levels in the dry season as well as declining groundwater tables (Adams and Smiley, 2018). Groundwater dynaMICS also have significant consequences for surface water security, playing a critical role in river flow (Kelly et al., 2020) and influencing Lake Malawi's water level (Kalin et al., *in prep*), further emphasizing their importance in the consideration of any aspect of Malawi's water resources. Understanding the nature of groundwater is therefore critical in guiding sustainable water policy. Yet, despite this significance, Malawi's groundwater resources remain largely understudied and misunderstood (Kalin et al., 2022).

Monitoring and appropriate management of Malawi's groundwater has been hampered by insufficient groundwater monitoring (Mleta, 2010; IGRAC, 2013; Kalin et al., 2022). There is little contiguous, reliable, and sustained data on groundwater management in Malawi (Kalin et al., 2022). Some of the barriers to reliable groundwater monitoring arise from challenges in infrastructure. Whilst Malawi currently has 71 groundwater monitoring wells nationally, the network of monitoring wells is troubled by vandalism and insufficient or failing equipment, e.g. data loggers (Kalin et al., 2022). Since construction of monitoring wells began in 2009, at least 10 are already known to be non-functional due to vandalism (Kalin et al., 2022). Monitoring is also not appropriately distributed with some regions having no groundwater monitoring, (Mleta, 2010), therefore limiting national level groundwater assessment. Even where infrastructure is available, regular monitoring is limited with data often not being appropriately downloaded and stored (Kalin et al., 2022). Challenges in appropriate data management and coordination of groundwater monitoring data has identified as barrier to monitoring not only within Malawi but across the Southern African Development Community (SADC) (IGRAC, 2013). Finally, with the earliest monitoring networks only being established in 2009, even where reliable data is available, insight into long-term groundwater trends cannot be provided (Kalin et al, 2022). Consequently, understanding of the current quantity of, and historic trends in, Malawi's groundwater storage is greatly lacking. The only available national estimate of Malawi's water resources applies a water balance method and places Malawi's groundwater storage as between 96.7 and 1,108 km^3 (not including the saturated thickness of each aquifer unit) (Kalin et al, 2022). Anecdotal evidence points to sustained groundwater decline impacting water access (personal correspondence), however, there is currently no data to support this. National level and long-term data is needed to inform decision making and guide water management. The lack of understanding of both quantity and trends in groundwater availability limits effective and informed policy making.

Hydrological modelling can provide a system to fill this knowledge gap. Through simulating water resource dynaMICS, hydrological modelling can inform understanding of current water resources as well as forecast future hydrological scenarios (Chen et al., 2021). By modelling both groundwater and surface water dynaMICS, these models have potential to provide holistic water resource understanding. However, many large-scale models fail to adequately simulate groundwater flow (Gnann et al., 2023; Guillaumot et al., 2022; Kollet and Maxwell, 2008; Kraft et al., 2022), particularly failing to simulate lateral flows of groundwater between cells which are essential for proper groundwater representation (Guillaumot et al., 2022). Inadequate spatial resolution of large-scale modelling further holds back effective modelling efforts by limiting model performance, particularly of groundwater (Guillaumot et al., 2022; Reinecke et al., 2020). These constraints particularly limit appropriate modelling of water table depth (Guillaumot et al., 2022; Reinecke et al., 2020) which is essential in the consideration of groundwater resources and groundwater change.

Ensuring appropriate representation of human demand of water resources has been another area of development in recent efforts to progress hydrological modelling, the Community Water Model (CWatM) is a key example of this progress (Burek et al., 2020). CWatM is a distributed global hydrological model that creates models of water resource management and human impact on water resources, integrating both surface and groundwater (Burek et al., 2020). Crucially, through water demand modelling, the model enables simulation of both environmental processes alongside human activity, making it particularly valuable to explore water management scenarios. Whilst under the default set-up of the CWatM model, there is no lateral flow within groundwater (Guillaumot et al., 2022), integration of the CWatM model with the three-dimensional finite-difference groundwater flow model MODFLOW (version 6) (Langevin et al, 2017; Guillaumot et al., 2022) enables improved groundwater modelling and redistribution allowing holistic water resource modelling.

Within Malawi, hydrological models have been used to develop understanding of water resources and inform policy (Bhave et al., 2022, 2020)**.** Whilst valuable, such models have been largely restricted to surface water (Bhave et al., 2020; Calder et al., 1995; Drayton, 1984; Neuland, 1984) or been limited to water balance approaches (Kumambala, 2010; Lyons et al., 2011; Shela, 2000) with limited value to informing holistic, and particularly groundwater-based, water resource understanding. Where detailed groundwater specific modelling studies have been conducted in Malawi, these have been on sub catchment level (Sehatzadeh, 2011) and are unable to respond to national level calls for increased groundwater understanding. Applying global hydrological models to develop understanding of national level water resources can provide a beneficial tool to develop understanding where limited information on water resources is available (Chavarría et al., 2022). However, global hydrological models can often exhibit poor performance on the national or basin level, particularly in areas where there is limited in situ data (Chavarría et al., 2022). Equally, the models may exhibit poor local relevance. This presents a paradox in that many of the areas where global hydrological models can be most beneficial to fill knowledge gaps, they may also exhibit poorest model performance.

Stakeholder co-production approaches can provide a vital method to enhance contextually relevant hydrological modelling, not only demonstrating good practice in hydrological modelling (Eden et al., 2016) but also overcoming some of the challenges in hydrological models inadequately capturing local level water resource dynaMICS (Chavarría et al., 2022). By integrating multiple stakeholder perspectives, a more comprehensive and locally relevant conceptualisation of water resources can be developed (Eden et al., 2016). Incorporating different perspectives within the modelling process is an important component of an effective coproduction process, ensuring diverse knowledge representation (Cho et al., 2023; Eden et al., 2016; Megdal et al., 2017; Villamor et al., 2019). In addition to the benefits for model performance, co-production approaches, integrating stakeholders into model generation, can result in the generation of hydrological models with improved credibility and more useful model outputs (Bhave et al., 2020). Co-production can, therefore, enhance both the usefulness of the product and, potentially, the adoption rate of model informed policy recommendations; it should be noted that many other barriers persist in ensuring effective policy impact (Landström et al., 2023).

In this study, we apply the global hydrological model CWatM, coupled with MODFLOW groundwater modelling, (Burek et al., 2020; Guillaumot et al., 2022) to an understudied water resource area, exploring how stakeholder informed production can enhance hydrological modelling in a data-scarce region. Taking the context of Malawi's water resources, the study not only develops vital understanding of water resources challenges in the region, but also enhances understanding of how global hydrological models can better represent water resources in other Sub-Saharan African basins. By developing a stakeholder informed model, we explore the potential of stakeholder-informed modelling to meet the challenge of representing local level water resource dynaMICS (Chavarría et al., 2022), providing relevant information (Megdal et al., 2017), and guiding useful model outputs (Bhave et al., 2020). By comparing model performance of a 'default' calibrated model performance for the basin alongside that of a 'stakeholder-informed' calibrated model, the capacity for stakeholder-informed modelling to enhance model performance is evaluated. Development of a basin-wide hydrological model, specifically one that couples groundwater and surface water, then enables development of the understanding of Malawi's groundwater, directly responding to calls for enhanced understanding of groundwater resources (Kalin, 2022).

Specifically, this study addresses the following research questions:

1) Can stakeholder-informed hydrological models better represent water resources within a sub-Saharan African basin?
2) What is the status of Malawi's groundwater resources and how have this changed in recent years?

2. Methodology

2.1 Context and study area

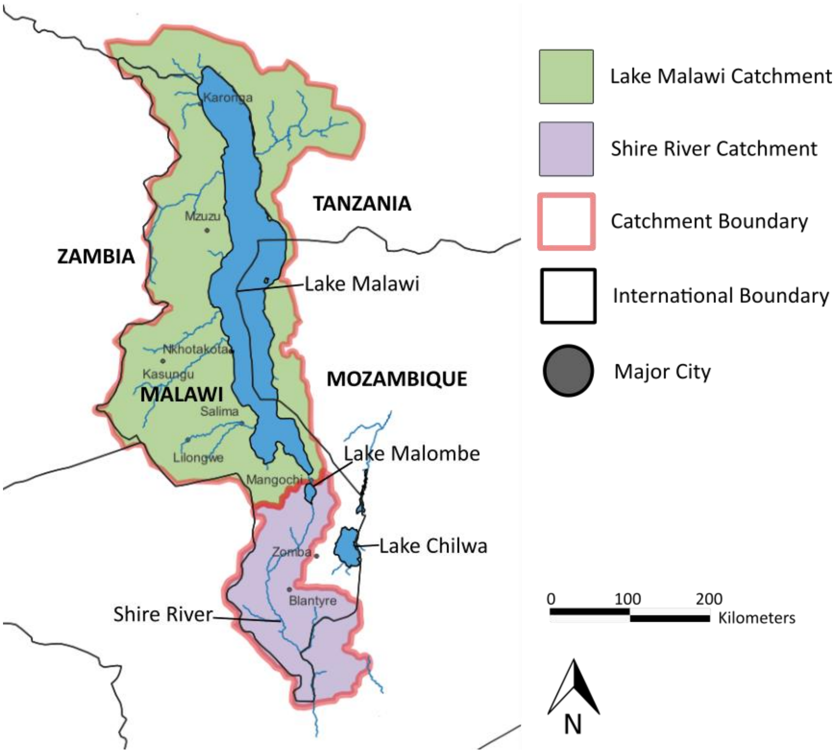

Figure 3: Study area, the transboundary Lake Malawi Shire River Basin (LMSRB) covering 94% of Malawi's surface area. The Lake Malawi catchment and Shire River catchment are shown in green and purple respectively. Makor lakes and cities are marked.

This study focuses on the Lake Malawi Shire River Basin (LMSRB), a catchment made of the Lake Malawi basin and the Shire River basins (Figure 1). The LMSRB is the most downstream sub-basin of the Zambezi River Basin, with outflows from Lake Malawi and the Shire River joining the Zambezi River downstream in Mozambique (Shela, 2000). The LSMRB covers approximately 94% of Malawi's land area, with the remaining 6% falling within the Lake Chilwa drainage basin, it is therefore central to Malawi's water security (Nhamo et al., 2016). Whilst the LMSRB lies mostly within Malawi, the LMSRB is a transboundary system with ~21% of the catchment lying in Tanzania and ~10% in Mozambique (Bhave et al., 2020). As the LSMRB dominates Malawi's water resources, this study focuses on water management scenarios within Malawi and their influence on the basin's hydrology.

The region has a mild tropical climate with a rainy season (November to April), in which it is estimated that 95% of precipitation falls (Streefkerk et al., 2022), and a dry season (May to October) (Vincent et al., 2014). Throughout the dry season (May-October), groundwater plays a particularly important role in sustaining river flows, making up to 97% of river flow through baseflow (Kelly et al., 2019). Seasonal variation in Malawi's hydrology is also exhibited in seasonal wetlands (dambos) that delay groundwater baseflow expression by buffering precipitation events (Kalin et al., 2022). Within the LSMRB, Lake Malawi is the biggest storage of surface water, with a volume of 8,400km^3. The Kamuzu barrage, built in 1965, regulates lake outflow to the Shire River, controlling both Lake Level and contributing to flood control (Sehatzadeh et al., 2017).

Malawi's land and water use is dominated by agriculture, with 64.2% of land area being used for agriculture in 2021 (World Bank, 2024). The majority of agricultural land is used as cropland, making up 47.75% of total land area use in 2019 (Li et al., 2021); accurately representing the nature of agriculture and crop growth within a model is critical. A large portion of agricultural land within Malawi is used for smallholder, subsistence agriculture; 80% percent of Malawi's population are estimated to be subsistence farmers (NPC, 2020). Smallholder farmers typically operate rainfed agriculture, however, smallholder irrigation has been significantly increasing (Mapemba et al., 2020); an estimated 41,053 hectares of Malawian smallholder land was under irrigation in 2016, rising to 59,655 hectares in 2019 (Chafuwa, 2017; Government of Malawi, 2019). Expansion of smallholder irrigation has been specified as a critical priority by the Government of Malawi, with a target of an annual 2% growth in smallholder irrigation (Wiyo and Mtethiwa, 2018). Since 2004, smallholder irrigation has been growing at half of this target (1% annual growth) (Wiyo and Mtethiwa, 2018). However, the type of irrigation system varies between commercial and smallholder farms. Whilst commercial farms typically implement high-cost irrigation technologies such as motorised sprinkler systems (Wiyo and Mtethiwa, 2018), irrigation systems used by smallholder farmers generally are gravity-fed systems (47%), treadle or motorized pumps (43%) (Government of Malawi, 2019; Wiyo and Mtethiwa, 2018), and watering cans (10%) (Government of Malawi, 2019).

2.2 Stakeholder engagement

This work sits within an ongoing process of stakeholder engagement spanning over 20 years, forming part of a partnership between the Scottish Government and Malawian Government under the Climate Justice Fund Water Futures Program. Ongoing work has developed understanding of groundwater and surface water resources, notably resulting in a revised Groundwater Atlas which has contributed to the much of the conceptual understanding of the water dynaMICS within this paper (Kalin et al., 2022).

Directed stakeholder consultation was sought to guide the modelling process, enabling the development of a model more relevant to the context and tailored to stakeholder needs. Three key stakeholders were identified from both governmental and non-governmental organisations and provided personal opinions and perspectives on water management in Malawi. The organisations were Baseflow, a non-governmental Malawian groundwater social enterprise; the National Water Resources Authority (NWRA), a government-appointed body monitoring and managing water resources; and the Ministry of Water and Sanitation. These organisations were selected to provide engagement with both governmental and non-governmental organisations, to interrogate a range of opinions and approaches to water management, and to gain expertise from sources representing the spectrum of actors involved in Malawi's water.

Stakeholder engagement was conducted through semi-structured interviews. The interviews focused on gaining insight into what stakeholders perceived to be significant considerations for water management, particularly focusing on groundwater, both currently and in the future. During interviews, the overall model structure of CWatM was discussed, stakeholders were encouraged to comment on the model structure, identifying gaps and areas where the model should be tailored to the context. Space was also given for stakeholders to identify areas where future hydrological modelling would be most beneficial. The interview questions, through which these comments were collected, are provided in the Supplementary Information. Following stakeholder interviews, feedback was evaluated and categorised into thematic groups.

2.3 CWatM Model Initalisation and Modification

This research used the open-access, hydrological Community Water Model (CWatM) (Burek et al., 2020). The CWatM enables the integration of multiple hydrological processes and water management scenarios. Both the default and stakeholder model were run at a high resolution of 5-arc minutes (approximately 10km at the equator) for the basin. The representation of Lake Malawi within the CWatM was modified for both models to account for the presence of the Kamuzu Barrage and regulated lake outflow which has significant implications for river flow. A regular discharge, different in the dry and wet season, as a proportion of the lake volume was set based on literature estimates (Bhave et al., 2020).

The model was run from 1965-2009. The start date of model simulation was determined as after the construction of the Kamuzu Barrage, built in 1965 (Sehatzadeh et al., 2017). The end data of simulation was determined due to the availability of consistently measured historical meteorological data for 1900-2009. The first 15 years of simulation were used as a 'spin-up' period to establish the groundwater table and results from 1980-2009 are evaluated here.

A stakeholder informed model was developed based on stakeholder feedback and knowledge surrounding the hydrological context. Figure 2 provides an overview of the use of stakeholder feedback in the modelling process of both the ‘default’ and ‘stakeholder informed’ models. The areas of modification are summarised in Table 1.

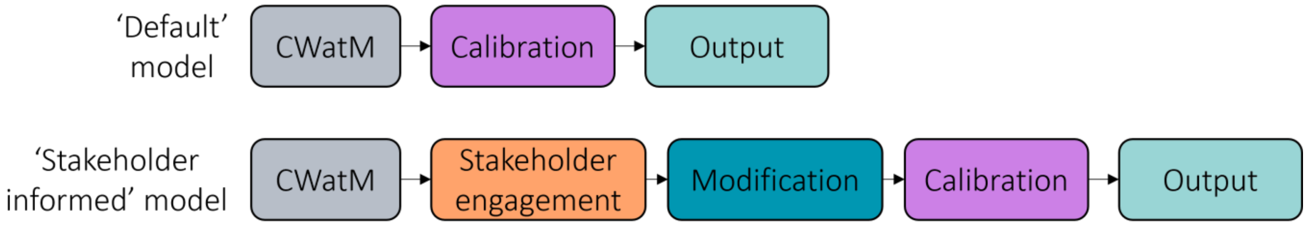

Figure 2: Incorporation of stakeholder engagement into the modelling structure showing the difference in the ‘default’ and ‘stakeholder informed’ models used within this piece. Stakeholder engagement took the form of semi-structured stakeholder interviews focused on how to represent Malawi’s water resources.

Table 1: Areas of modification identified by stakholders and literarature and methodology for modification. Modifications primaruly from stakeholder enagament are marked with an asterisk (*) whilst modifications primarily from literature are marked with a delta (Δ).

Area of modification	Modification	Rationale	Method of modification
Hydrological / geomorphological representation	Groundwater lateral flow *, Δ	Within the CWatM model, there is no lateral flow within groundwater (Burek et al., 2020). This particularly holds back modelling of groundwater table depth.	The CWatM hydrological model was coupled with the three-dimensional finite-difference groundwater flow model MODFLOW at 5km resolution to as outlined by Guillermont et al., 2022 (Langevin, 2017; Guillaumot et al., 2022).
	Aquifer properties Δ	Aquifer porosity and thickness impact groundwater flow regimes, particularly influencing groundwater-surface water dynaMICS (Kalin et al., 2022). Porosity and thickness vary between aquifer types.	A shapefile of the three main aquifer units in the study area was generated to capture the dynaMICS of the hydrogeology of the study area (Kalin et al., 2022). The main aquifer units considered were: consolidated sedimentary rock units, unconsolidated sedimentary units overlying a weathered basement, and weathered basement units overlying fractured basement. Based on literature estimates, aquifer porosity and thickness estimates were set for each aquifer type (Kalin et al., 2022) and used to create a heterogeneous raster file of aquifer thickness and porosity. The given values selected for the aquifer units are summarised in Table 2.
	Wetlands/ Dambos Δ	'Dambos' (wetlands with hydromorphic soils) act to retain water (Kalin et al., 2022; von der Heyden, 2003) thereby strongly influencing groundwater dynaMICS and surface water flows.	To simulate the water retention within wetlands, a wetland shapefile was generated using satellite imagery to identify areas as wetlands. In wetland areas, the channel gradient was reduced and the channel length was increased to simulate longer water retention times within these areas.
Water management	Domestic water abstraction source (groundwater vs surface water) *	There is significant variation in the source of domestic water use in urban and rural areas with a more substantial reliance on groundwater in rural areas. Groundwater is estimated as the main water source for domestic use for 82.3% of the rural population and 19.8% of the urban population (Chavula, 2012).	A raster file for the basement was developed at 5 arc minute resolution. Regions within Malawi were categorised as urban or rural. In urban areas 80% of water demand was assumed to be met by surface water (reservoirs) and the remaining 20% from groundwater. Within rural areas 20% of water demand was met from surface water (reservoirs) and the remaining 80% was supplied from groundwater.

Domestic water demand *	Urban areas have high per capita water consumption rates (mainly due to differences in sanitation and hygiene practices). Rural per capita daily water requirement is estimated at 36L (Mkondiwa et al., 2013) whilst the urban requirement (taking the case of Blantyre City), is estimated as 152L (Maoulidi, 2012).	A raster file of Malawi's population divided by rural and urban areas (Hinton et al., *in review*) was multiplied by estimates of domestic water withdrawal and consumption requirements for urban and rural populations. Rural consumption was assumed to be 36 L/person/ day whilst urban consumption was assumed to be 152 L/person/day.
Irrigation *	Over 80% of the population of Malawi practise smallholder farming (NPC, 2020), making smallholder agriculture an important consideration in land management. Due to the seasonality of precipitation, most agriculture in the dry season requires irrigation (Mapemba, 2020).	The percentage of land used for smallholder farming was taken from IFPRI Harvest Choice estimates (Koo et al., 2020). We assume that 5% of smallholder land is irrigated (to the same intensity as commercially irrigated farmland). It was assumed that irrigation was evenly distributed among all land with smallholder agriculture. To account for the increase in irrigated cropland, land classified (land use raster file) as grassland was selected for reclassification to irrigated cropland.
Sanitation (pit-latrines) *	The majority of the population of Malawi uses pit latrines as their primary sanitation source (Hinton et al., 2023). Wastewater is assumed to be discharged into river systems in CWatM; however, in the case of pit-latrines this wastewater enters soil systems and into groundwater storage.	Where pit-latrines are used, wastewater is routed to enter groundwater recharge rather than be discharged into rivers. The percentage of the population using pit latrines was added as an additional variable, by default this is set to 92% (Hinton et al., 2023).

Table 2: Aquifer properties of three most common aquifer types. Data from Kalin et al., 2022 (with permission).

Aquifer unit	**Porosity/%**	**Thickness/m**
Consolidated sedimentary rock units	10	50
Unconsolidated sedimentary units overlying weathered basement	25	35
Weathered basement units overlying fractured basement	5	25

2.4 Validation and calibration

Basin-wide scale model validation was undertaken by comparing model outputs with remote sensing observations of precipitation and evapotranspiration, the major input and output (respectively) within the model. These were obtained for the study area using Google Earth Engine (Gorelick et al., 2017). Daily precipitation estimates were obtained from the TRMM 3B42 (Huffman, 1997; Huffman, 2012; Huffman et al., 1997; Huffman et al., 2007; Hufman et al., 2001; Huffman et al., 1995). Meanwhile, 5 evapotranspiration remote sensing datasets, at varying temporal and spatial resolutions, were used for comparison: NASA GLDAS (Rodell et al., 2004), MODIS 500m (Running and Mu, 2015), Terraclimate (Abatzoglou et al., 2018), NASA SMAP (Reichle et al., 2022), and PML_V2 (Zhang et al., 2019; 2016; Gan et al., 2018). The PML_V2 estimate breaks down evaporation into 3 components (Ec, Ei, and Es), to evaluate total evaporation these were summed (Zhang et al., 2019; 2016; Gan et al., 2018).

Manual model calibration was achieved through comparison on observed and simulated streamflow. River flow data was provided by the Government of Malawi, Ministry of Water and Sanitation. Monitoring stations on 35 rivers, representing all regions of Malawi, were selected for comparison. Only monitoring stations with more than 15 years of data were utilised. Where multiple monitoring stations were available for a given river, the monitoring station furthest downstream was selected. The monitoring stations and rivers are summarised in Appendix Table 1 alongside the dates for which measured streamflow data was available. Ten major rivers were identified as particularly important monitoring stations and are highlighted in bold. The locations of the discharge stations (with major river discharge stations labelled) is shown in Figure 1.

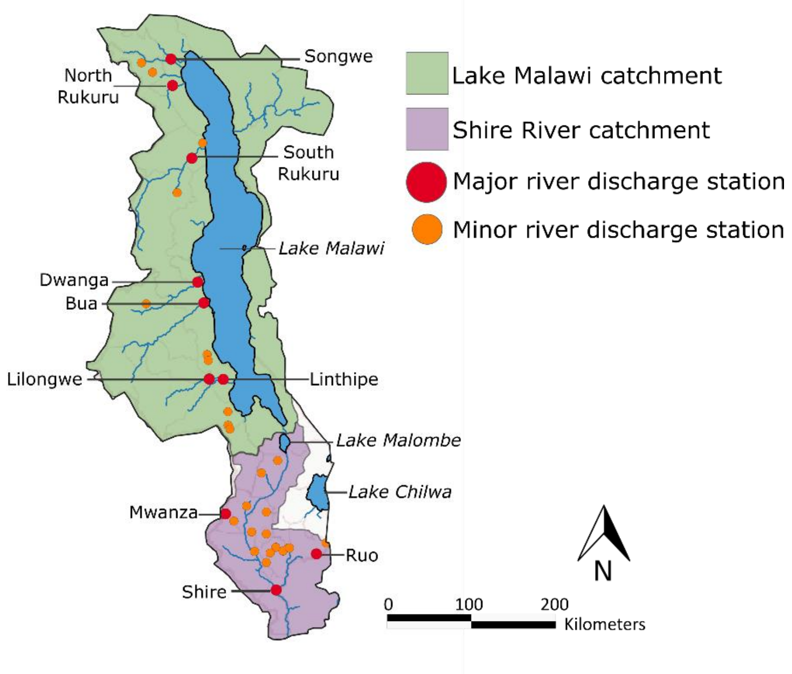

Figure 4: Study area, Lake Malawi Shire River Basin. Discharge monitoring stations used in this study are shown.Major stations are highlighted in red and the river they correspond to it labelled.

Model performance, comparing simulated to observed streamflow, was calculated using the Kling-Gupta Efficiency (KGE) in equation 1.

$$KGE = 1 - \sqrt{(r-1)^2 + (\frac{\mu_s}{\mu_o} - 1)^2 + (\frac{\sigma_s/\mu_s}{\sigma_o/\mu_o} - 1)^2} \; (1)$$

Where r is the pearson coefficient, $\mu_s$is the mean streamflow of the simulated time series, μ_o is the mean streamflow of the observed time series, σ_s is the standard deviation of the simulated data, and $\sigma_o$is the standard deviation of the observed data.

A KGE value >-0.4 was taken as adequate model predictive performance of stream flow (Elmi et al., 2024). To evaluate the model performance of the default model in comparison to the stakeholder informed model, KGE values at the 35 national monitoring stations were compared, evaluating the number of discharge stations in which streamflow was adequately represented.

2.4 Total water storage

Changes in the total water storage, the volume of water stored within all surface water, groundwater, and soil systems, were evaluated in the models. Remote sensing estimates via the Gravity Recovery and Climate Experiment (GRACE) satellites were used to validate variations in the total water storage of the basin (Swenson, 2012; Landerer and Swenson, 2012; Swenson and Wahr, 2006). The GRACE total water storage estimates analysed differences in total water storage compared to the average total water storage from 2004-2009. To enable validation with GRACE satellite data, the total water resources for the basin modelled through CWatM were compared to the average modelled estimates from 2004-2009. Three different datasets of GRACE data from three processing centres were used: JPL (Jet Propulsion Laboratory), GFZ (GeoforschungsZentrum Potsdam), and CSR (Center for Space Research at University of Texas). Total water storage change measured by GRACE was compared to the default and stakeholder informed models.

To evaluate the fit of the simulated data to the GRACE data, four goodness of fit indices were employed to better capture the difference characteristics of GRACE data in comparison to the simulated TWS (Akl and Thomas, 2022): the Kling-Gupta Efficiency (KGE), Root Mean Squared Error (RMSE, Nash-Suttclife Efficiency (NSE), and the Spearman Correlation (SC) (Akl and Thomas, 2022). These indices, summarised in Equations 1-4, were used to evaluate the performance of the default and stakeholder informed CWatM models.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\mu_i - \widehat{\mu_i})^2} \quad (2)$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{N}(\mu_i-\widehat{\mu_i})^2}{\sum_{i=1}^{N}(\mu_i-\bar{\mu})^2}\right] \quad (3)$$

$$SC = \frac{\sum_{i=1}^{N}(\mu_i-\bar{\mu})(\widehat{\mu_i}-\ddot{\mu})}{\sqrt{\sum_{i=1}^{N}(\mu_i-\bar{\mu})^2\sum_{i=1}^{N}(\widehat{\mu_i}-\ddot{\mu})^2}} \quad (4)$$

Where N is the number of data points, μ_i is the measured streamflow and $\widehat{\mu_i}$ is the predicted streamflow, $\bar{\mu}$ is the mean measured streamflow, and $\ddot{\mu}$ is the mean predicted streamflow.

2.4 Groundwater Storage

The model with the best performance was selected based on the number of discharge stations adequately simulated as well as identifying the model with the best overall performance, across multiple indices, for simulation of GRACE TWS data. The total groundwater storage was also evaluated for the model with best performance. To estimate the equivalent groundwater table height (m), the total volume of groundwater (m^3) was divided by the total basin surface area (m^2). Simulated groundwater storage from 1980-2009 was analysed to evaluate groundwater storage change over time.

3. Results

3.1 Stakeholder engagement

All stakeholders identified the influence of a growing population, and meeting the domestic water requirements of such a population, as a critical consideration for current and future water management. There was a consensus among stakeholders that, even assuming a 'constant' water supply, the growing population will result in falling water resources per capita, pushing Malawi closer to water scarcity. The difference in water demand (both volume and source) within urban and rural areas was also identified as a critical consideration in national water demand dynaMICS. To meet future domestic water demand within urban areas, plans have been developed to expand surface water abstraction through further dam construction and, notably, by proposed developments to pipe water from Lake Malawi to meet the growing water requirements of Lilongwe City (Lilongwe Water Board, 2018). Proposals to pie water from Lake Malawi to Lilongwe city were mentioned multiple times by stakeholders as essential considerations in future water management: *"If it works, it may change the landscape of water supply*".

Within the context of domestic water management, the type of sanitation used was acknowledged to influence both (ground)water abstraction, as water demands vary between sanitation infrastructure, and groundwater recharge. Sanitation was also highlighted as a significant driver within water quality due to faecal water contamination (Hinton et al., *in review;* Graham and Polizotto, 2013). It was even suggested that this could also influence the demand for groundwater/ piped surface water, with the potential for people to prefer piped water sources as sanitation infrastructure may contaminate groundwater sources.

The interface between surface water and groundwater was also mentioned as a significant factor in understanding Malawi's water resources. The importance of considering both groundwater and surface water in Malawi's water systems (Kelly et al., 2020) was also emphasised: "*Groundwater is vital to river systems*".

Agriculture was also identified as an important consideration in water management in Malawi due to water use in irrigation (NPC,2020; Mapemba et al., 2020). The impact of agriculture on water management in Malawi was discussed as distinct for commercial agriculture compared to smallholder agriculture through the differences in irrigation previously discussed. Planned developments to increase the extent of commercial agriculture and the generation of 'mega farms' was mentioned by stakeholders as being a critical consideration for Malawi's future water demand (NPC, 2020).

However, the importance of accounting for smallholder irrigation and smallholder agriculture within models of water management in Malawi was identified as a critical component of modelling Malawi's water resources given the extent of smallholder agriculture, practiced by over 80% of the population (NPC, 2020). Stakeholders iterated that the majority of smallholder farmers practice rainfed, subsistence agriculture and do not have intensive irrigation, as seen in more commercial farming sectors (Mapemba et al., 2020). It was highlighted that smallholder farmers do implement some irrigation systems to enable agriculture during the dry season when there is limited precipitation: *"almost all smallholder farmers practice some form of irrigation, especially during the dry season".* It was mentioned that a growing push towards solar-powered pumps for groundwater abstraction, increasing capacity for year-round irrigation as well as enabling groundwater abstraction in areas where it was previously unfeasible, may have important consequences for groundwater abstraction.

It should be noted that land use and agricultural land management changes also have implications for groundwater recharge. Industry was also mentioned as an area of water abstraction that is highly connected with agriculture. Climate change and deforestation were both mentioned as factors influencing groundwater recharge within Malawi but were mostly discussed when considering future influences on groundwater management. The importance of catchment restoration, reforestation, and alternative groundwater recharge initiatives was highlighted as a potential future policy intervention in groundwater management.

The areas of modulation identified by stakeholders and sourced by literature are summarised in figure 3.

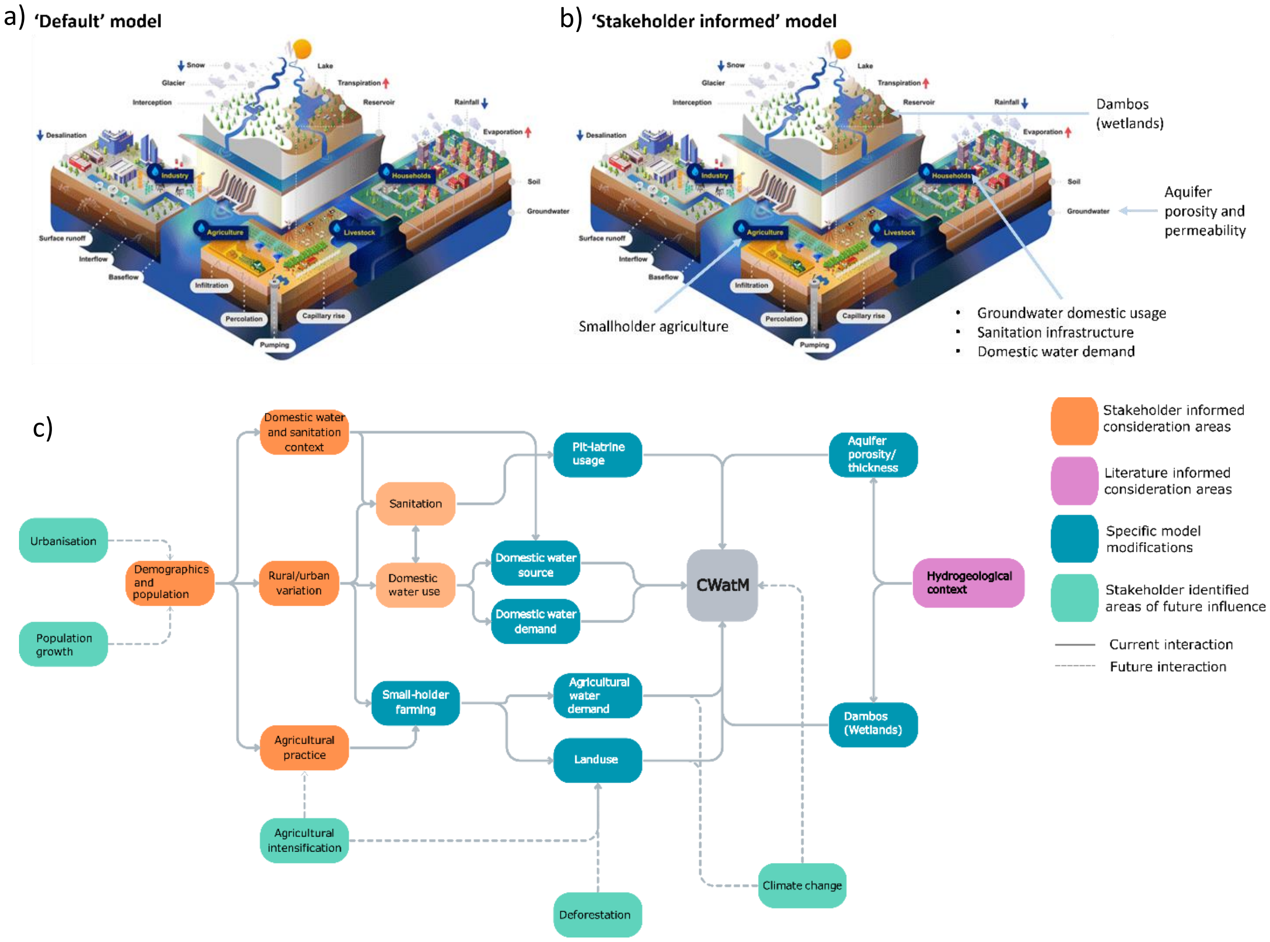

Figure 5: Areas of modification identified by stakeholders and literature. a) shows the structure of the CWatM model used as the 'default model' here. b) Shows the CWatM model with areas of modification in the 'stakeholder informed model' as identified by stakeholders and literature. c) Shows the specifc areas of modification of the stakeholder informed model, specifying where areas/ themes for modification were identified from (literature and stakeholder enagagement). Specific model modifications relate to modifications outlined in table 1. Areas identified for future modification/ model development are also shown. Model structure (a and b) from Burek et al., 2020.

3.2 Model performance

The major model inputs and outputs were identified as precipitation and evapotranspiration (Supplementary Data, Figure 1). Basin-wide validation of evapotranspiration and precipitation was conducted by comparison to remote sensing data and was considered appropriate, figures are provided in Supplementary Information Figures 2 and 3.

Streamflow predictive performance was used to evaluate model performance through the Kling-Gutpa Efficiency (KGE). Table 3 summarizes the model performance at predicting streamflow for 35 discharge stations nationally. Cases where the streamflow was inadequately predicted (KGE< -0.4) (Elmi et al., 2024) are marked with an asterisk. Major rivers are highlighted in bold. The average KGE value for all monitoring stations under the original model was -0.5263, under the stakeholder informed model the average KGE value was -0.2206.

Table 3: Model performance streamflow simulation of discharge stations. Cases where streamflow was inadequately modelled (KGE<-0.4) are marked by an asterix. Major river discharge stations are shown in bold.

Observation station code	River	KGE value original model	KGE value stakeholder informed model
1C1	Lirangwe	0.116	0.0860
1E1	Mwamphanzi	0.019	-0.393
1E19	Mudi	-0.224	-0.234
1F17	Livunzu	0.218	0.304
1G1	**Shire**	**-0.011**	**-0.183**
1K3	**Mwanza**	**-0.248**	**-0.206**
1M1	Mkurumadzi	-0.0770	-0.828*
1O1	Lisungwe	-0.479*	-0.0248
1R3	Rivirivi	-0.232	-0.00822
1S7	Nkasi	-0.174	-0.109
3E2	Namikokwe	0.273	0.285
3E3	Livulezi	-0.371	-0.0394
3F3	Nadzipulu	-0.0300	-0.0995
4B1	**Linthipe**	**0.150**	**0.407**
4C2	**Lilongwe**	**-0.593***	**-0.255**
5C1	**Bua**	**-0.158**	**0.210**
6C5	Mpasadzi	-1.87*	-0.335
6D10	**Dwanga**	**-2.25***	**-1.23***
7D8	Lunyangwa	-0.104	0.163
7G14	**South Rukuru**	**-1.51***	**-0.0472**
7H3	North Rumphi	-3.47*	-2.97*
8A5	**North Rukuku**	**-0.0607**	**0.0717**
9A5	Kalenje	-3.57*	-2.846*
9B3	Kaseye	-0.718*	-0.125
9B7	**Songwe**	**0.535**	**0.399**
14A1	Namadzi	-0.954*	-0.0567
14A2	Luchenza	-0.133	0.0635
14B1	Kwakwasi	-2.08*	-0.323
14B2	Thuchila	-0.113	0.359
14B4	Nswadzi	-0.197	0.0569
14C2	**Ruo**	**-0.293**	**-0.287**
14C7	Muloza	0.307	0.304
15A4	Chirua	-0.306	-0.0844
15A8	Lingadzi	0.203	0.309
16E6	Dwambadzi	-0.0286	-0.0554

3.3 Total Water Storage

Total water storage was calibrated against GRACE data. A comparison of GRACE data to total water storage data under 4 goodness of fit metrics (Akl and Thomas, 2022) is summarised in Table 4. For NSE, KGE, and RMSE, the stakeholder informed model provided better predictions of total water storage change for all sources of GRACE data (CSR, GZP, and JPL). The default model had higher Spearman correlation for all sources of GRACE data. Both models under predicted the extend of annual fluctuations in total water storage.

Table 4: Goodness of fit of simulated total water storage and GRACE remote sensed estimates of total water storage. The model with the best peformance for the given goodness of fit index and source of GRACE data is highlighted in bold. Overall the stakeholder-informed had better performance for NSE, KGE, and RMSE whilst the default model perfomed better for Spearman Correlation.

Model	Goodness of fit index	GRACE CSR	GRACE GZP	GRACE JPL
Default	NSE	0.222	0.224	0.222
	KGE	-6.89	-2.56	-4.18
	RMSE/ cm	0.902	1.22	1.14
	Spearman correlation	**0.513**	**0.530**	**0.488**
Stakeholder informed	NSE	**0.302**	**0.306**	**0.301**
	KGE	**-5.36**	**-2.35**	**-3.42**
	RMSE/cm	**0.871**	**1.11**	**1.08**
	Spearman correlation	0.500	0.516	0.475

As the stakeholder informed model had better model performance for streamflow data and for GRACE data comparison, it was used to evaluate the groundwater storage change. The change in

TWS compared to GRACE data for the stakeholder informed model is summarised in supplementary information.

3.4 Malawi's groundwater resources

The change in Malawi's groundwater resources was evaluated using the stakeholder informed model, as this had better model performance for simulating discharge data and TWS. The change in groundwater storage is shown in Figure 4.

From 1980-2010, there was a decrease in groundwater storage from an average of 670.4 km3 in 1980 to 652.5 km3 in 2009 (end), this represents a 17.83 km3 reduction over 30 years and a loss of 2.66% of total groundwater storage from 1980. This corresponds to an initial equivalent groundwater table depth of 4.27m for 1980 falling to 4.15m by 2009, representing an 11.4 cm average drop in groundwater table depth over the 30 years and an average decline of 3.79mm/

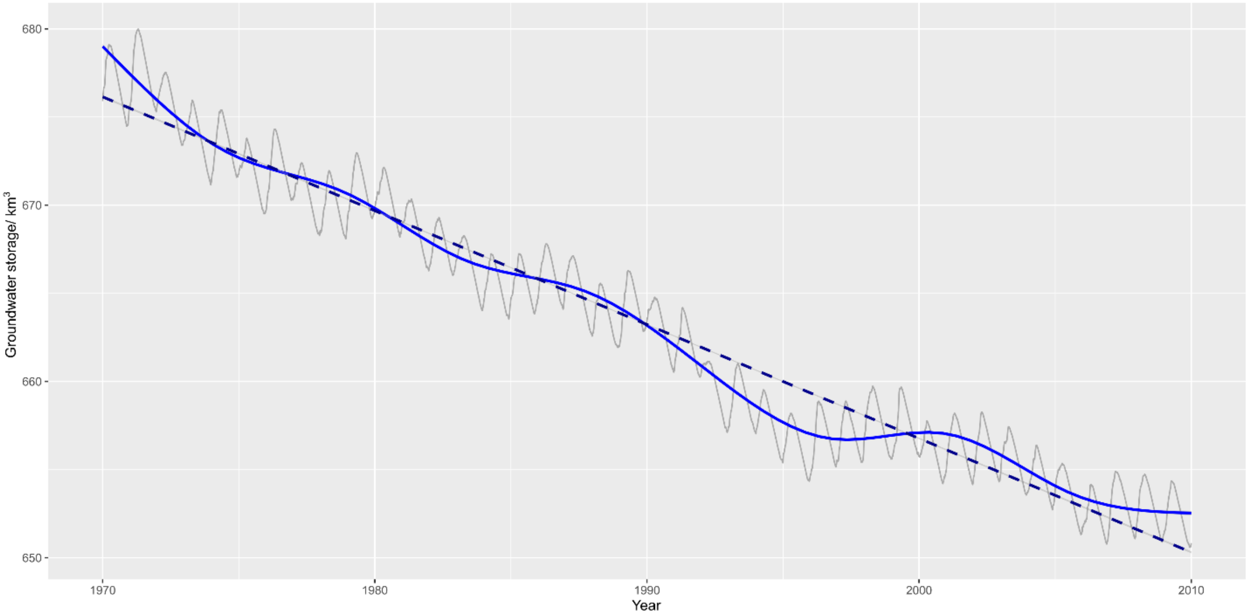

Figure 4: Change in groundwater storage (km3) from 1980- 2009 (end). Simulated groundwater storage is shown as grey line. Trends in groundwater storage is shown in blue, loess (solid blue), linear trend (blue dashed).

year. A constant linear trend line is fitted (R^2= 0.908) as well as a local regression (loess) trend line, span 0.75.

4. Discussion

4.1 Stakeholder informed model of water resources

Hydrologic modelling can provide a valuable tool to enhance understanding of both current and future water resources (Chen et al., 2021). It can be of particular benefit in areas where *in situ* data is limited due to logistical or resource constraints (Chavarría et al., 2022). Groundwater is an aspect of water resource management that can be particularly hard to monitor and manage, typically requiring significant investment to develop groundwater monitoring wells which subsequently require continuous management to ensure maintenance and gather data (Kalin et al., 2022; IGRAC, 2013). In regions where there is limited groundwater monitoring data, hydrologic models provide a way to fill the knowledge gap. Yet, despite the potential benefits of appropriate modelling of water resources, particularly groundwater, many hydrologic models perform poorly in understudied regions (Chavarría et al., 2022) and few appropriately model groundwater resources (Guillaumot et al., 2022).

Malawi is a context in which enhanced understanding of groundwater resources is greatly needed. Despite groundwater being a central component of Malawi's water system, accounting for over 80% of domestic water use (Graham and Polizotto, 2013), both the quantity and trends in Malawi's groundwater storage are largely unknown (Kalin et al., 2022). The lack of understanding of groundwater is largely due to an inadequate network of monitoring wells, which limit current monitoring, as well as there being no historic measurements of groundwater data (Kalin et al., 2022). Anecdotal evidence suggests that groundwater levels have been declining, with some areas experiencing a drop of 1m groundwater/ year (personal correspondence), however, such data is unable to guide national level policy decisions. Such a lack of understanding of groundwater greatly restricts the ability for policy decisions to be sufficiently informed as well as effective water management in general within Malawi.

Here, we apply to global Community Water Model (CWatM) to the Lake Malawi Shire River Basin (LMSRB) to inform understanding of Malawi's water resources (Burek et al., 2020).

Covering 94% of Malawi’s land area and accounting for most of its water storage, the LMSRB is the most significant basin for Malawi’s water resource management. Previous studies have simulated critical components of the LMSRB (Bhave et al., 2020; 2022; Sehatzadeh, 2011) but no study has yet developed a model of the basin’s groundwater storage. To better account for these gaps and inform national policy, the model was coupled with the groundwater flow model MODFLOW to better simulate groundwater dynaMICS (Guillaumot et al., 2022). The model was calibrated with discharge data from monitoring stations on 35 rivers nationally and validated with remote sensing data of evapotranspiration, precipitation, and total water storage. The model failed to adequately simulate river flow in 29% of rivers generally and 30% of Malawi’s (10) major rivers, limiting inference into the model outputs.

Stakeholder engagement was used to inform and enhance modelling of Malawi’s water resources. A stakeholder informed modelling approach was used to modulate the CWatM to better represent Malawi’s water context through a series of semi-structured interviews and identification of areas for modulation. The stakeholder informed model incorporated context specific modification of hydraulic properties (groundwater representation, aquifer properties, and the presence of wetlands/ ‘dambos’) alongside water management representation (domestic water demand and source, sanitation, and agricultural practices). Model performance for the stakeholder informed model was compared to the default model structure (both calibrated and with MODFLOW and the Kamuzu Barrage representation). Overall, the stakeholder informed model had much improved model performance; the stakeholder model adequately predicted 89% of all discharge station streamflow data and 90% of the streamflow at discharge stations on the major rivers.

These findings suggest that stakeholder informed modelling approaches are not only good practice in hydrological modelling (Eden et al., 2016), resulting in better implementation of policy recommendations and findings (Basco-Carrera et al., 2021), but can lead to better model performance through improved representation of local water resource dynaMICS. The work highlights that this approach can have particular benefit in understudied regions where hydrological models may perform the worst and yet are needed the most (Chavarría et al., 2022). The modifications highlighted in this work provide key learnings not only for more effectively modelling of Malawi's water resources but also prove consequential for modelling other basins within Sub-Saharan Africa. Some of the modifications of note for modelling similar basins are the inclusion of small-holder agriculture irrigation, pit-latrine sanitation systems, and dambos (wetlands).

4.2 Evaluation of model performance

Of the 35 major stations used for measured and simulated streamflow comparison, streamflow at only 1 station was inadequately represented in both the default and stakeholder informed models, station 6D10 on the Dwanga river. The station is located within Water Resource Area (WRA) 6, an area featuring many dambos/ seasonal wetlands (Kalin et al., 2022b)**.** The default model consistently underpredicted water flow within this station, with simulated streamflow falling to approximately 0 over the dry season and resulting in poor model performance. This is likely due to an underrepresentation of baseflow within this region which, on average, accounts for 97% of river flow in the dry season in Malawi (Kelly et al., 2020). The stakeholder informed model generated a model modification to simulate dambos (seasonal wetland areas), these geographic features increase water retention and, consequently, baseflow in these regions (Kalin et al., 2022; von der Heyden, 2003). This resulted in an improvement in streamflow representation for the two monitoring stations within WRA6, stations 6C5 and 6D10 on the small Mpasadzi and large Dwanga rivers respectively. For station 6C5 on the Mpadzi river, this modification resulted in substantial model improvement, from inadequate streamflow prediction under the default model to adequate prediction under the stakeholder informed model. However, after noting the modification, station 6D10 on the Dwanga river had an overprediction of streamflow and inadequate model performance, suggesting there was too strong a simulated influence of dambos at this station. Despite both models having inadequate prediction of streamflow data, the stakeholder informed model did have an improved predictive power, suggesting that the incorporation of wetland/ 'dambo' areas is beneficial for water resource modelling. Further work should build upon the representation of dambos within this model, particularly with regard to the potential for heterogeneous representation of wetlands influence to improve model performance in other contexts.

The change in TWS (total volume of water stored in surface water, groundwater, and soil systems) was also evaluated for both models to evaluate model performance. This was compared to remotely sensed estimates of TWS from GRACE satellite data (Swenson, 2012; Landerer and Swenson, 2012; Swenson and Wahr, 2006). For each model (default and stakeholder informed), simulated TWS was compared to GRACE satellite data estimates of total water storage using four goodness of fit metrics to better capture dynaMICS in TWS and GRACE data (Akl and Thomas, 2022). The stakeholder informed model had improved fit with the GRACE data than the default CWatM simulation, with NSE values of 0.30-0.31 and 0.22 for the stakeholder informed model and default models respectively. The NSE value of the default model indicated inadequate performance whilst the improved NSE value of the stakeholder informed model is in line with literature estimates of moderate performance for GRACE data (Tangdamrongsub et al., 2015). However, both models did not fully capture the dynaMICS of TWS measured by the GRACE data, with both underpredicting extremes in annual TWS change.

This may be partially due to the inherent challenges of applying GRACE data on the LMSRB due to the very significant impact of Lake Malawi on TWS.

Overall, the stakeholder informed model had better model simulation of both discharge and GRACE total water storage estimates than the default CWatM simulation, however, further development could enhance the representation of both dynaMICS of streamflow and TWS.

4.3 Simulating groundwater resources

Prior to this work, the only estimate of Malawi's groundwater resources applied a water balance methodology to estimate Malawi's groundwater storage as between 96.7 and 1,108 km^3 (not including the saturated thickness of each aquifer unit) (Kalin et al., 2022). We used the stakeholder informed model to investigate Malawi's groundwater resources due to its improved model performance. The model estimated 653 km^3 of groundwater storage in Malawi at the end of 2009, falling within the range proposed by Kalin et al. (2022). We show that there has been a reduction in groundwater storage by 17.83 km^3 over 30 years, representing a 2.66% reduction in storage from 1980 and a reduction in groundwater storage of almost 1% each decade. The annual reduction in groundwater storage of 0.594km^3/ year is a loss of approximately a third of the volume of Malawi's second largest lake, Lake Chilwa, every year.

Declining groundwater storage poses a significant challenge for Malawi's future water availability, likely resulting in an increase in boreholes facing non-functionality or seasonal water scarcity (Andres et al., 2018). Non functionality of boreholes is already a pressing issue for Malawi's water security, with 40% of boreholes partially/ totally nonfunctional or abandoned (Kalin et al., 2019). Meanwhile, high levels of seasonal water shortage further limit water access, with 34.5% of boreholes under 10m depth experiencing seasonal water shortages for one month or more per year (Kalin et al., 2019).

Fluctuations in groundwater storage between the wet and dry seasons, which result in changes in seasonal water availability, are on average 2-5km^3 annually, with an equivalent annual change in equivalent groundwater table depth of 1.3-3.2 cm. The current fluctuations in groundwater storage seen on an annual basis, that result in seasonal water scarcity, are significantly less than total change in equivalent groundwater table depth those observed from 1980-2009 of an 11.4 cm average drop in groundwater table depth. Each decade, Malawi has a drop in the average groundwater storage table (3.8cm) that is more than is witnessed in even the most extreme seasonal fluctuations (3.2cm), this creates cause for concern considering that such seasonal fluctuations currently result in more than 10% of boreholes experiencing seasonal water shortages and over 30% less than 10m deep (Kalin et al., 2019). Sustained and continuous depletion of groundwater storage in Malawi may result in many boreholes currently experiencing seasonal water shortages having more prolonged periods of water shortage, whilst boreholes with current year-round access may begin to experience seasonal water availability.

Interannual fluctuations in groundwater storage were also observed, with decadal fluctuations in storage likely reflecting long-term metrological patterns of rainfall and solar intensity. This has been observed specifically within Lake Malawi where groundwater storage change contributes to changes in lake level (Kalin et al., *in prep*). Further investigation of patterns in groundwater storage will be vital for appropriate groundwater management and policy.

4.4 Methodological limitations and future work

This study explores water dynaMICS within a transboundary basin, the LMSRB, as a representation of Malawi's water resources. Due to the focus of the work being motivated by close stakeholder consultation with partners within Malawi, the model production and calibration for *in situ* data, as well as stakeholder engagement process, is tailored specifically to Malawi. This limitation is considered appropriate as 69% of the basin falls within Malawi. Furthermore, the modifications made, notably those relating to domestic water and sanitation as well as smallholder irrigation, are consistent with water resource management scenarios in the transboundary regions of Mozambique and Tanzania. The model data is used to provide insight into Malawi's water resources as 94% of Malawi's surface area falls within the basin, therefore dominating considerations in Malawi's water resources. As such, this study is considered appropriate for exploring Malawi's water resources. Future work should consider the transboundary nature of this basin and ensure transboundary cooperation in development of water resource management plans (Fraser et al., 2020).

The lack of national level groundwater monitoring stations limits the capacity for model calibration and validation of groundwater levels (Kalin et al., 2022). Remote sensing of TWS through GRACE data is utilised to provide some validation of groundwater storage, however, this was limited and does not model groundwater specific data. Model development with alternative meteorological data, extending beyond 2009, could enable some comparison to measured groundwater table depths, with the first groundwater monitoring available from 2009 (Kalin et al., 2022). However, even where groundwater table data is available it is highly limited with incomplete data and little sustained monitoring (Kalin et al., 2022; Mleta, 2010). Future work should consequently not only incorporate longer simulation to enable calibration with groundwater table depth but should also be coupled with improved *in situ* groundwater table monitoring.

Whilst we assign a linear trend to groundwater decline, estimating approximately a 1% decline in groundwater storage per decade, the long-term change in groundwater availability is likely to follow a non-linear trend; non-linear population growth in particular is likely to influence groundwater resources. Uncertainty in the future of water resources and a call for enhanced modelling of future scenarios of water resources in Malawi was emphasised by stakeholders. A need to better understand the implications of climate change scenarios on Malawi's water resources was expressed through interviews. Future work and model development should simulate future scenarios accounting for multiple scenarios of climatic and socioeconomic change. Future model development should also account for changes in government strategy and different policy scenarios, focusing particularly on agricultural development and irrigation policy scenarios, to provide a better framework for future water management scenarios.

The addition of dambo/ wetland areas improved model performance. Improved model performance was seen particularly in WRA6 (stations 6C5 and 6D10 on the Mpasadzi and Dwanga rivers) as well as WRA7 (Stations 7D8, 7G14 and 7H3 on the Lunyangwa, South Rukuru, and North Rumphi rivers respectively) and WRA5 (station 5C1 on the Bua River) which all had improved model performance under the stakeholder informed model. However, further improvements within the modelling of dambos/ seasonal wetlands are needed, this was seen in the case of modelling discharge at the Dwanga river where the addition of wetlands resulted in an overestimation of baseflow and inadequate model performance. Spatial heterogeneity in the simulated influence of wetlands could enable improved modelling.

Finally, model generation would benefit from enhanced model calibration schemes which enable automatic calibration. The model presented here underwent manual calibration which was less efficient than automated schemes and limited capacity for parameter analysis. Automated calibration was not conducted due to the incorporation of MODFLOW (Langevin et al, 2017), as the MODFLOW model is not able to run under specific conditions, therefore crashing under some parameter combinations. Further modelling efforts should enable model function even under unsuitable MODFLOW parameters to enable automated calibration and parameter analyses, such as sensitivity analysis.

4.5 Policy implications

Limited and largely anecdotal evidence within Malawi has long pointed to a growing concern about the diminishing groundwater table. Whilst this has created a stronger awareness of groundwater resources, a lack of estimates of groundwater storage that are both quantifiable and representative of Malawi nationally, rather than restricted to well-studied regions, have held back the formulation of appropriate policy and prioritisation of groundwater protection.

This work provides national level estimates of groundwater levels, emphasising the trend of diminishing groundwater storage. For long-term water security in Malawi, the growing risk of depleting groundwater must be an area of focus (Kalin et al., 2022). Water resource policy should account for groundwater decline, this will be particularly important due to the increase of agricultural water use as the extent of commercial farming increases (Wiyo and Mtethiwa, 2018).

Whilst this study provides evidence of groundwater decline, enhanced understanding of groundwater security will be needed to ensure sustainable water policy. Alongside computational modelling, as presented here, *in situ* monitoring of groundwater storage will be necessary to inform appropriate water management. Expansion of the limited national groundwater monitoring network should be promoted in national water policy (IGRAC, 2013; Mleta, 2010; Kalin et al., 2022).

An increased burden of borehole non-functionality due to seasonal and long-term water scarcity, directly resulting from groundwater table decline, is likely to threaten domestic water resources, which are heavily dependent on groundwater (Graham and Polizotto et al., 2013). Not only does groundwater depletion threaten domestic water security, a growing burden of borehole non-functionality presents a risk of 'stranded assets' and significant loss of investment in water infrastructure (Kalin et al., 2019). Engaging communities in local-level sustainable water management will be an important part of safeguarding water resources (Hinton et al., 2021). National water policy should consider the local level nature of borehole use, management, and functionality alongside the national challenge of groundwater protection.

5. Conclusion

Comparing model performance of a global hydrological model for Malawi under default conditions with a model modified according to stakeholder engagement revealed improved model performance where the model was informed by stakeholders. This not only adds weight to the influence of stakeholder engagement, as it resulted in better implementation of recommendations (Basco-Carrera et al., 2021), but also improved model performance. Notably, appropriate representation of water demand, including spatial variation in domestic water use and sanitation as well as small-holder farming, is an important consideration to better enable hydrological modelling, particularly for Sub-Saharan African basins.

Through the development of a context appropriate hydrological model, this work provides the first system modelled estimate of Malawi's groundwater resources, it notably reveals a worrying trend of a consistent decline in groundwater storage from 1980-2009 and a loss of approximately 1% of groundwater storage per decade. Malawi's future water resource management must address the growing challenge of groundwater insecurity to meet the water requirements of its growing population. As emphasised by stakeholders, "*Malawi will continue to be dependent on groundwater for some time to come*", protecting this vital resource must therefore be a priority: "*if we continue on the current trends, it will be tragic*".

Acknowledgements

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1. Supplementary Information

6.1 Semi-Structured Stakeholder Interview Questions

Purpose of survey: The purpose of this survey is to provide further information on policies and practices in groundwater management in Malawi. We will use this information to inform the development of a Malawi-specific model of water abstraction

and recharge by developing the global Community Water Model (CWatM) developed by IIASA.

Specifically, we are interested in developing future scenarios of water use which we will be able to combine with predictions of groundwater recharge to identify key areas where groundwater may be threatened by over abstraction in the future.

We would like your input regarding how the factors influencing groundwater usage are currently expressed within the CWatM model framework and how we might summarise different policy scenarios that you could envisage impacting future groundwater use.

Data availability:

We will be using the open access model CWatM (https://iiasa.ac.at/models-tools-data/cwatm**) to develop these scenarios (see the CWatM structure and inputs below.)**

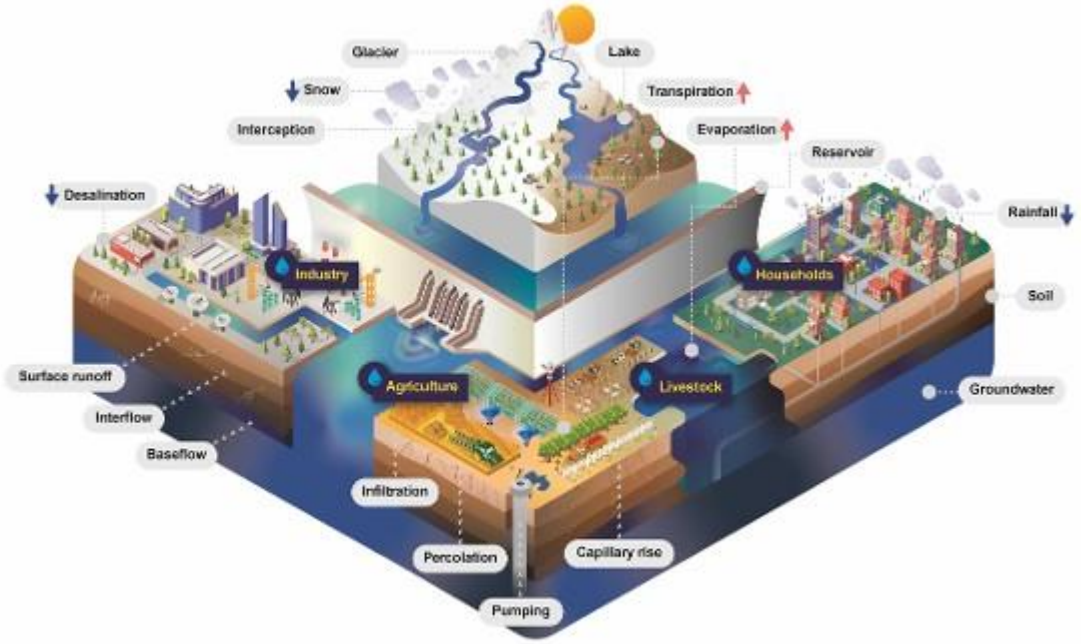


Figure 6: Overview of CWatM model

We **will also be also using data from the 2022 Groundwater Atlas for Malawi (Kalin et al. (2022) Hydrogeology and Groundwater Quality Atlas of Malawi, Bulletin, Ministry of Water and Sanitation, Government of Malawi).**

Introduction and ethical considerations (5´)

Purpose: We provide a very short introduction to the project (aim, duration, funder, partners), the purpose of the interviews, how these contents will be used and treated (data protection), and what is our role as interviewers in this process.

- Name of the interviewer and role, other persons in the call (if)
- Short project description: What is the CWatM model and how do we plan to improve the model of groundwater abstraction for a Malawian context?
- Purpose of the interview and expected duration (45-60 min max)
- Small rules for the interview:
    - Keep answers as concise as possible
    - Please notify the interviewer if any question is not clear
    - At the end of the interview there will be a few minutes for making comments and additional suggestions
- Permission for recording and managing personal following the EU data protection regulations (including the anonymization of individual responses)

Background information (5´)

Purpose: This section should allow us to gather information on the role of the interviewed in the WE nexus of the urban water cycle and the scale (regional or local)

1. What role do you and your organization play in groundwater management/ research in Malawi?

TOPIC I: Overall groundwater abstraction questions (10')

Purpose: Provide an overview of the CWatM model and identify any areas which are not representative of groundwater usage in Malawi.

2. What, in your view, are the most significant drivers of groundwater usage in Malawi?

3. Figure 1 provides an overview of the inputs of groundwater abstraction in the CWatM model, do you think this is representative of factors influencing water management in Malawi? Is there anything missing?

TOPIC II: Future scenarios of groundwater abstraction (10´)

Purpose: To determine some outlines of scenarios of future domestic water use to use in the CWatM model.

4. In your opinion, how do you think domestic groundwater usage will change in Malawi over the next 50 years?
5. What key policies and development plans, across sectors, are foreseen in the next 50 years that could most impact groundwater use in Malawi? Specific development plans or policies to refer to.
6. Do you have any recommendations or strategies that you think Malawi should explore in groundwater management over the coming years?

Comments and remarks (2-3´)

Purpose: give the chance to the interviewed to provide any additional comment or even feedback on the interview and the questions. In case we are searching for other stakeholders, we can use this section to inquire the interviewed for further contacts (snowball technique).

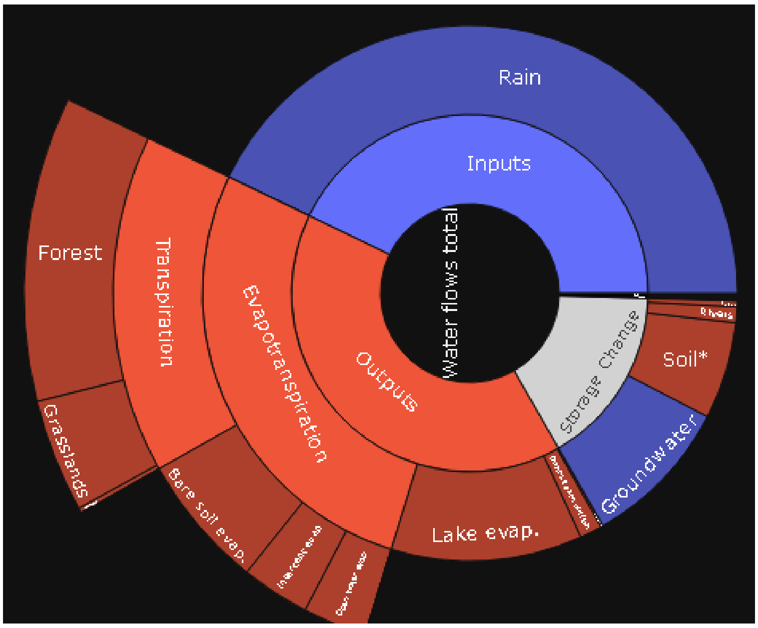
We should also inform here that once the interviews will be processed, everyone will receive the results of the assessment and they will have the opportunity to provide feedback

6.2 Discharge stations

Supplementary Information Table 1: Observation codes, rivers, and dates for discharge stations used in this study. Major rivers are highlighted in bold.

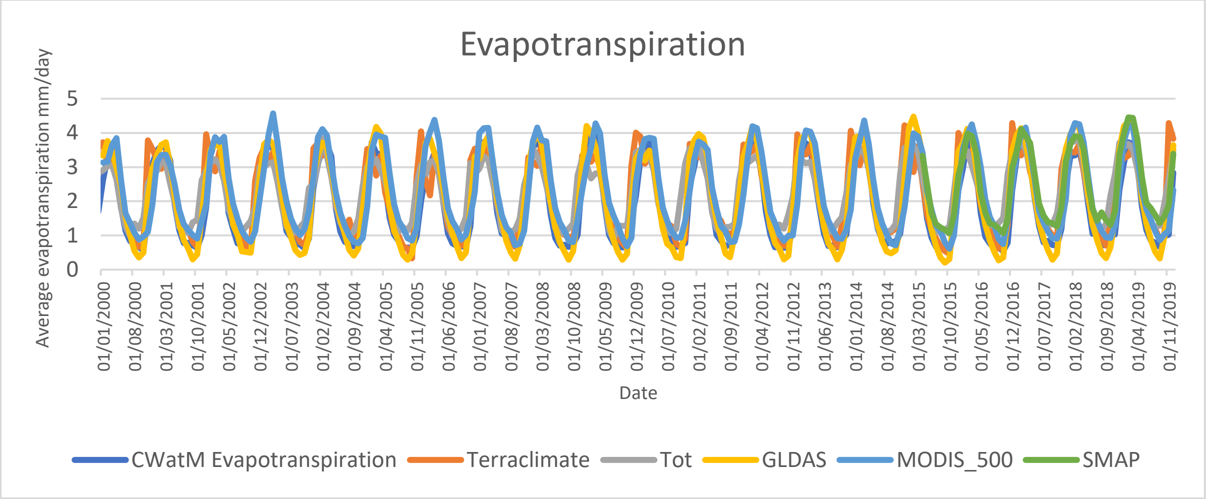
Observation station code	River	Observation start date	Observation end date
1C1	Lirangwe	11/04/1951	31/08/2005
1E1	Mwamphanzi	12/01/1951	24/03/2002
1E19	Mudi	21/11/1961	30/04/1993
1F17	Livunzu	07/03/1979	17/02/1997
1G1	**Shire**	**01/02/1953**	**31/12/2009**
1K3	**Mwanza**	**11/03/1970**	**31/08/2008**
1M1	Mkurumadzi	11/03/1980	27/08/2008
1O1	Lisungwe	12/02/1951	11/01/1970
1R3	Rivirivi	11/12/1952	31/08/2004
1S7	Nkasi	10/03/1961	31/01/1997
3E2	Namikokwe	12/03/1957	08/09/2003
3E3	Livulezi	19/10/1957	29/05/2008
3F3	Nadzipulu	31/08/1957	13/12/2003
4B1	**Linthipe**	**04/02/1953**	**16/06/2009**
4C2	**Lilongwe**	**20/11/1957**	**30/04/2010**
5C1	**Bua**	**11/03/1957**	**31/01/2010**
6C5	Mpasadzi	12/01/1965	30/09/2001
6D10	**Dwanga**	**01/03/1986**	**31/01/2010**
7D8	Lunyangwa	02/08/1954	30/06/2008
7G14	**South Rukuru**	**29/11/1957**	**25/05/2007**
7H3	North Rumphi	09/12/1972	31/05/2007
8A5	**North Rukuku**	**20/11/1968**	**31/05/2009**
9A5	Kalenje	11/12/1970	31/05/2007
9B3	Kaseye	28/06/1971	31/01/2008
9B7	**Songwe**	**08/06/1985**	**29/02/2012**
14A1	Namadzi	28/05/1971	31/03/1998
14A2	Luchenza	01/04/1955	31/10/2002
14B1	Kwakwasi	14/12/1951	31/08/1986
14B2	Thuchila	12/07/1951	30/12/2003
14B4	Nswadzi	11/03/1980	30/06/2002
14C2	**Ruo**	**07/02/1953**	**31/10/2008**
14C7	Muloza	01/03/1975	31/03/2002
15A4	Chirua	11/03/1970	31/10/2000
15A8	Lingadzi	22/07/1961	31/01/2010
16E6	Dwambadzi	03/11/1972	31/05/2009

6.3 Water balance

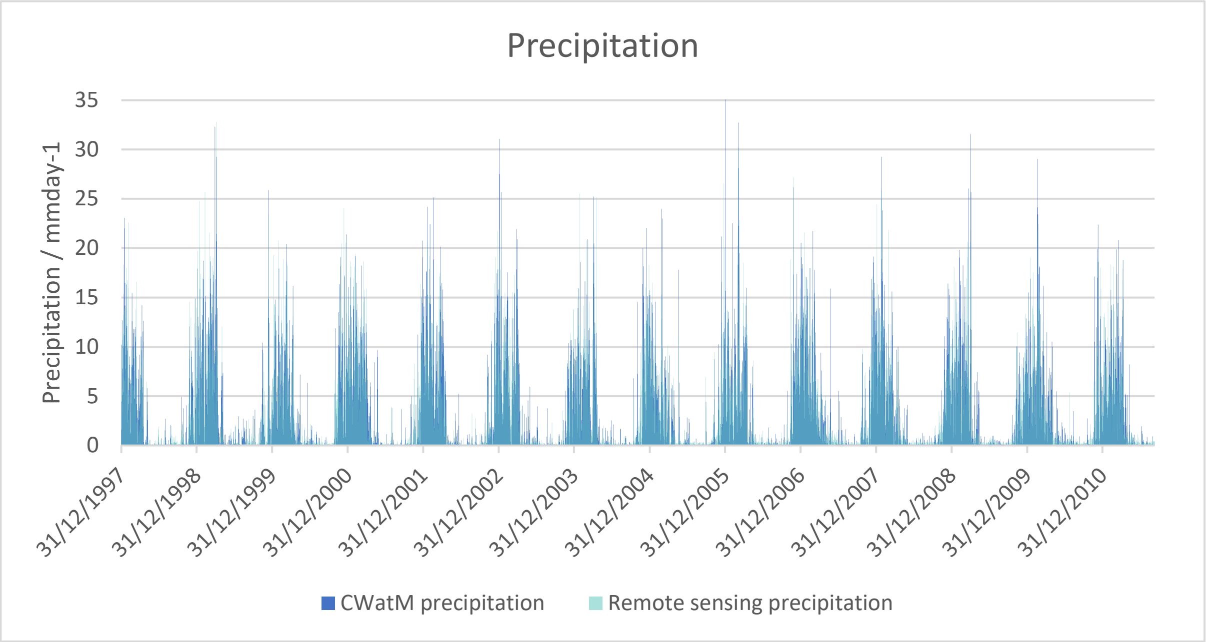


Supplementary Information Figure 1: Example water circle showing the balance of inputs and outputs into the water system for the period 01/01/1990- 01/07/1990. Water loss is shown in red and water increase is shown in blue.

6.4 Evapotranspiration and precipitation validation

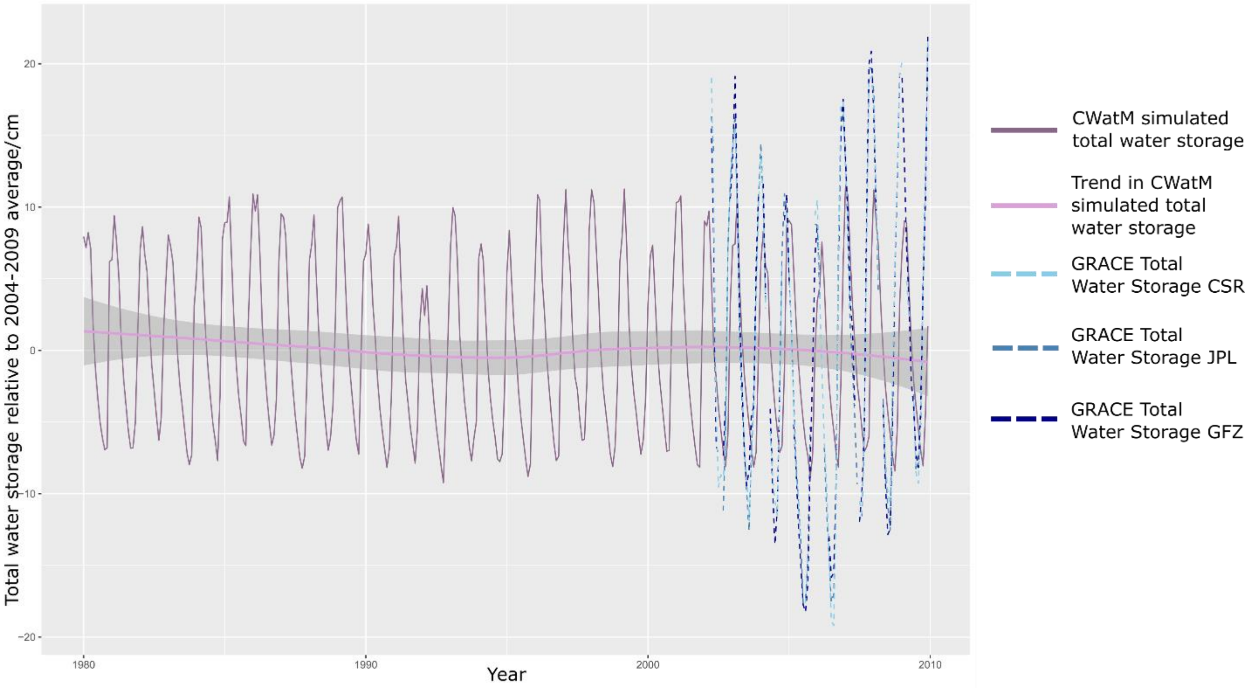


Supplementary Information Figure 2: Evapotranspiration validation. The graph compares the CWatM modelled evapotranspiration with NASA GLDAS [53], MODIS 500m resolution [54], Terraclimate [55], NASA SMAP [56], and the total sum of the 3 components of PML_V2 [57-59] (Tot) evapotranspiration estimates.



Supplementary Information Figure 3: Precipitation validation. The CWatM precipitation data and Remote sensing precipitation estimation (TRMM 3B42 [46-52] dataset) are compared. Overall, patterns of precipitation and magnitudes are consistent between the CWatM precipitation data and remote sensing estimates.

6.5 Total Water Storage



Supplementary Information Figure 4: Total water storage change 1980-2009 (end) within the stakeholder informed CWatM simulation. Comparison to GRACE data is provided.

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4.3.1 Postface

This work generated the first system modelled estimates of Malawi’s groundwater resources, thereby providing essential information to guide water policy decisions. Developing a water model that accounts for groundwater dynaMICS through coupling a global water model (CWatM) with MODFLOW generated improved modelling compared to previous models of water resources where previous models either fail to account for groundwater dynaMICS or apply only a water balance approach (Bhave et al., 2019; Calder et al., 1995; Drayton et al., 1984; Neuland et al., 1984; Kumambala et al., 2010; Shela et al., 2000; Lyons et al., 2011). Providing model modifications to reflect the context of Malawi resulted in improved model performance and a more representative model of Malawi’s water resources than previously available. In addition, through modeling groundwater resources over time, a national decline in groundwater storage was evidenced and quantified for the first time. The decline in groundwater storage supports anecdotal evidence of local groundwater table declines and stories of boreholes running dry due to depleting water resources (personal correspondence). This work added greater emphasis to the criticality of groundwater consideration and its protection for Malawi’s future water security.

This paper directly responded to RQ1 through achieving SO2 and developing a model of groundwater storage in the LMSRB. This was used to achieve SO3 and explore how groundwater availability has changed over recent years, identifying the growing challenge of groundwater depletion to Malawi’s water scarcity. This piece also identified the challenge of groundwater depletion to water scarcity in Malawi.

4.4 Conclusion to this chapter

This chapter addressed RQ1 'What are challenges to water scarcity in Malawi?' A methodology to explore the implications of groundwater for surface water in Malawi was presented through investigating how Lake Malawi's storage is impacted by groundwater (SO1). Lake Malawi was shown to be impacted by groundwater change, emphasising how any consideration of water security in Malawi must account for groundwater. Information surrounding challenges to Malawi's groundwater, and an investigation of scarcity, was developed through the generation of a holistic, stakeholder informed hydrological model for Malawi (SO2). The model provided not only an improved and novel investigation of Malawi's water resources but also provided insight into hydrological modelling in other sub-Saharan African basins. Through modelling Malawi's groundwater resources, a trend of declining national groundwater storage was evidenced for the first time, raising concerns for future water scarcity (SO3).

These results present a grave concern for Malawi's water scarcity challenge. Assuming a constant level of water resources, Malawi has already been rapidly plummeting towards absolute water security, Figure 10. Yet the research presented in this chapter presented a perhaps even more worrying projection of falling water resources. The combinatorial challenges of declining water resources and growing demand present a potential crisis of water scarcity raising concerns that Malawi may reach absolute water scarcity even sooner than originally thought.

However, water scarcity must be considered alongside other challenges in securing 'clean water for all' and achieving SDG6, notably water quality must be considered alongside water scarcity to ensure water security.

The next chapter considers challenges to water provision in Malawi from water quality as part of ensuring 'clean water access' within SDG6.

4.4.1 SDG6 targets explored in this chapter

This chapter primarily addressed the SDG6 targets shown in Figure 4.2: SDG6.1 ‘safe drinking water for all’, SDG6.4 ‘water scarcity and water-use efficiency’ and SDG6.6’ Protect and restore water related ecosystems’ which emphasises the need for protection of both aquifers and lakes, which are addressed within this chapter. In addition, this chapter also highlighted some of the challenges facing a transboundary water system, thereby enhancing understanding towards SDG6.5 ‘integrated water management and transboundary cooperation’.

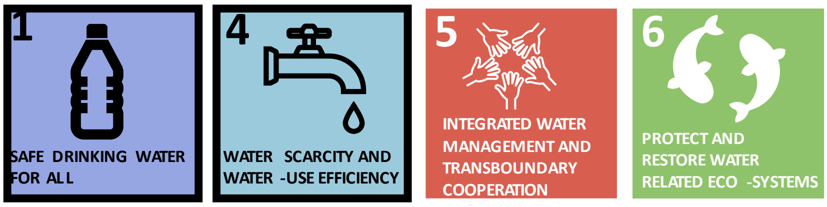


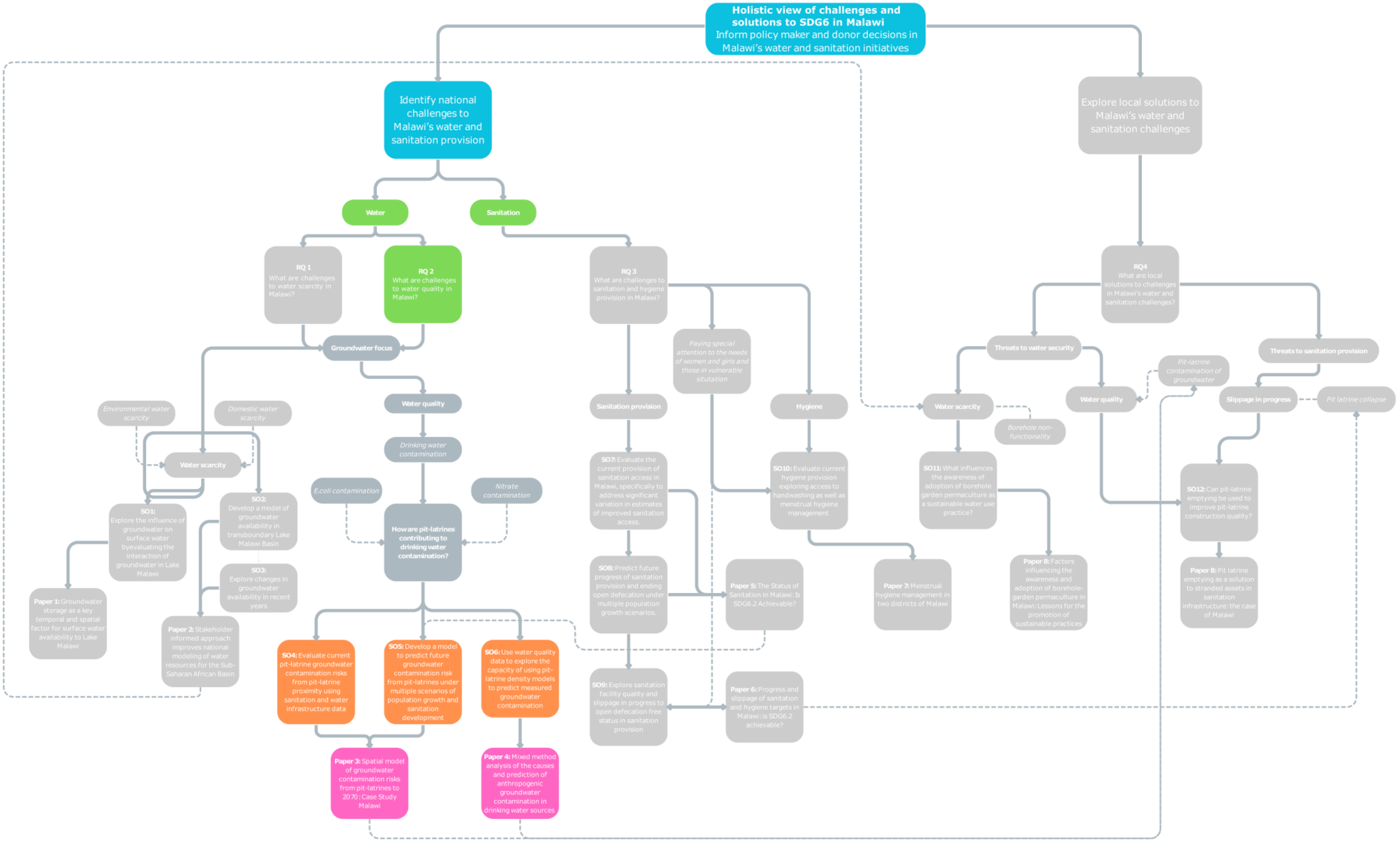
Figure 4.2: SDG6 targets addressed within this chapter. The chapter primarily focuses on SDG6.1 ‘safe drinking water for all’ and SDG6.4 ‘water scarcity and water-use efficiency’.

Chapter 5: Challenges of water quality for SDG6

"Anadabwa madzi ateyesa mkhosi"

Chichewa expression

Though the water appears clean it is not safe


Holistic view of challenges and solutions to SDG6 in Malawi
Inform policy maker and donor decisions in Malawi's water and sanitation initiatives
Identify national challenges to Malawi's water and sanitation provision
Explore local solutions to Malawi's water and sanitation challenges
Water
Sanitation
RQ 1 What are challenges to water scarcity in Malawi?
RQ 2 What are challenges to water quality in Malawi?
RQ 3 What are challenges to sanitation and hygiene provision in Malawi?
RQ4 What are local solutions to challenges in Malawi's water and sanitation challenges?
Groundwater focus
Environmental water scarcity
Domestic water scarcity
Water scarcity
SO1: Explore the influence of groundwater on surface water byevaluating the interaction of groundwater in Lake Malawi
SO2: Develop a model of groundwater availability in transboundary Lake Malawi Basin
SO3: Explore changes in groundwater availability in recent years
Paper 1: Groundwater storage as a key temporal and spatial factor for surface water availability to Lake Malawi
Paper 2: Stakeholder informed approach improves national modeling of water resources for the Sub-Saharan African Basin
Water quality
Drinking water contamination
E.coli contamination
Nitrate contamination
How are pit-latrines contributing to drinking water contamination?
SO4: Evaluate current pit-latrine groundwater contamination risks from pit-latrine proximity using sanitation and water infrastructure data
SO5: Develop a model to predict future groundwater contamination risk from pit-latrines under multiple scenarios of population growth and sanitation development
SO6: Use water quality data to explore the capacity of using pit-latrine density models to predict measured groundwater contamination
Paper 3: Spatial model of groundwater contamination risks from pit-latrines to 2070: Case Study Malawi
Paper 4: Mixed method analysis of the causes and prediction of anthropogenic groundwater contamination in drinking water sources
Paying special attention to the needs of women and girls and those in vulnerable situtation
Sanitation provision
Hygiene
SO7: Evaluate the current provision of sanitation access in Malawi, specifically to address significant variation in estimates of improved sanitation access.
SO8: Predict future progress of sanitation provision and ending open defecation under multiple population growth scenarios.
SO9: Explore sanitation facility quality and slippage in progress to open defecation free status in sanitation provision
SO10: Evaluate current hygiene provision exploring access to handwashing as well as menstrual hygiene management
Paper 5: The Status of Sanitation in Malawi: Is SDG6.2 Achievable?
Paper 6: Progress and slippage of sanitation and hygiene targets in Malawi: is SDG6.2 achievable?
Paper 7: Menstrual hygiene management in two districts of Malawi
Threats to water security
Water scarcity
Borehole non-functionality
Water quality
Pit-latrine contamination of groundwater
SO11: What influences the awareness of adoption of borehole garden permaculture as a sustainable water use practice?
Paper 8: Factors influencing the awareness and adoption of borehole-garden permaculture in Malawi: Lessons for the promotion of sustainable practices
Threats to sanitation provision
Slippage in progress
Pit latrine collapse
SO12: Can pit-latrine emptying be used to improve pit-latrine construction quality?
Paper 8: Pit latrine emptying as a solution to stranded assets in sanitation infrastructure: the case of Malawi

Chapter 5: Challenges to water quality for SDG6

5.1 Introduction

Chapter 4 considered challenges surrounding water quantity (RQ1) for Malawi in reaching SDG6. However, alongside quantity, the quality of water is an equally critical consideration in ensuring water security (Grey and Sandoff, 2007). The significance of water quality is particularly important in considerations for human consumption and clean drinking water provision. However, elevated contamination levels pose substantial ecological concerns, underscoring the need for holistic approaches to water management that address both quantity and quality concerns.

This chapter will answer RQ2, 'What are challenges to water quality in Malawi?'. As in the case of Chapter 4, this chapter focuses on the challenge of groundwater security due to its pivotal role in Malawi's water resources, particularly domestic water use. A major challenge to clean water provision in Malawi is a high level of faecal water contamination; 60% of the population's source of drinking water has *E.coli* contamination (NSO, 2021). This presents a significant public health concern due to the associated consequences of waterborne disease stemming from poor water quality. Inadequate access to water, sanitation, and hygiene (WASH) services has been identified as a major contributor to more than half (52%) of the disease burden in the country (UNICEF, 2021). Diarrheal diseases, often originating from contaminated water sources, are responsible for 7% of deaths among children under five in Malawi (Moon et al., 2019). Recently, a lack of adequate WASH facilities, exacerbated by extreme flooding, resulted in Malawi experiencing its most severe cholera outbreak in 2023, leading to 8,982 reported cases of cholera and 1,768 deaths (WHO Malawi, 2023) and, emphasising the importance of waterborne disease prevention.

The challenge of high levels of water contamination is exacerbated by low access to water treatment; 64.6% of the population lacks access to any form of water treatment (NSO, 2021). Among those with access to treatment, the most prevalent method utilized is bleach chlorination, employed by 25.2% of the population, despite its low efficiency and the World Health Organization's general recommendation against its use (NSO, 2021; Nielsen et al., 2022). Even where treatment is implemented to manage microbial contaminant risks, it is ineffective at removal of chemical contaminants such as nitrate within groundwater which present environmental and public health hazards Puckett et al., 2011.; Rahman et al., 2021). Managing the challenge of high levels of faecal water contamination therefore requires management of the sources of contamination. Faecal waste is a particularly pressing source of groundwater contamination making consideration of the contamination risks to groundwater from sanitary infrastructure essential to securing water security and progress to SDG6.

This chapter focuses on the risk of groundwater contamination from sanitation infrastructure, evaluating current challenges as well as the future threats to groundwater quality. The emphasis on sanitation as a significant anthropogenic source of contamination has direct consequences for policy emphasising how holistic consideration of sanitation **and** water within SDG6 is imperative.

Specifically, this chapter responds to the research question: RQ2: What are challenges to groundwater quality in Malawi?

Through addressing the specific objectives:

SO4: Evaluate current pit-latrine groundwater contamination risks from pit-latrine proximity using sanitation and water infrastructure data.

SO5: Develop a model to predict current and future groundwater contamination risk from pit-latrines under multiple scenarios of population growth and sanitation development.

SO6: Use water quality data to explore the capacity of using pit-latrine density models to predict measured contamination of groundwater drinking water supplies.

This chapter is made up of two papers submitted, or under draft for submission, to international peer-reviewed journals. The papers are:

Paper 3

Hinton R.G.K., Kalin, R.M., Kanjaye, M.B., Mleta, P., Macleod, C.J.A., Trolborg, M. (*In Review*). Spatial model of groundwater contamination risks from pit-latrines under multiple sanitation scenarios in a low-income country. *Water Resources*.

Author contribution:

Conceptualization (R.G.K.H, R.M.K, C.J.A.M, M.T, M.K), data curation (K.M, P.M, R.M.K), formal analysis (R.G.K.H), investigation (R.G.K.H), methodology (R.G.K.H), validation (R.G.K.H), visualization (R.G.K.H), project administration (R.M.K), supervision (R.M.K, C.J.A.M, M.T), writing original draft (R.G.K.H), review and editing (R.G.K.H, R.M.K., C. J.A.M, M. T, M. K, P.M)

Paper 4

Hinton, R.G.K., Kalin., R.M., Banda., L., Kanjaye, M., Macleod, C. J. A., Troldborg, M., Phiri, P., Kamtukule, S. (*In Review*) Mixed method analysis of anthropogenic groundwater contamination of drinking water sources in Malawi. *Science of the Total Environment*

Author contribution:

Conceptualization (R.G.K.H, R.M.K, L.B.) data curation (R.G.K.H, L.B, R.M.K., M.K., P.P., S.K), formal analysis (R.G.K.H, L.B.), investigation (R.G.K.H, L.B), methodology (R.G.K.H, L.B), validation (R.G.K.H, L.B), visualization (R.G.K.H, L.B), project administration (R.M.K), supervision (R.M.K, C.J.A.M, M.T), writing original draft (R.G.K.H), review and editing (R.G.K.H, L.B, R.M.K., C. J.A.M, M. T, M. K, P.P., S.K.)

It should be noted that section 2.7 of the methodology and section 3.6 of the results of paper 4 were written by co-authors Limbikani Banda and Robert Kalin.

5.2 Spatial model of groundwater contamination risks from pit-latrines under multiple sanitation scenarios in a low-income country

Rebekah G.K. Hinton[1,2], Robert M. Kalin[1], Modesta B. Kanjaye[3], Prince Mleta[4], Christopher J. A. Macleod[2], Mads Troldborg[2]

[1]Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow G1 1XJ, UK

[2]The James Hutton Institute, Craigiebuckler, Aberdeen AB15 8QH, UK

[3]Director of Sanitation and Hygiene, Ministry of Water and Sanitation, Government of Malawi, Private Bag 390, Lilongwe, Malawi

[4] Director of Water Supply, Ministry of Water and Sanitation, Government of Malawi, Private Bag 390, Lilongwe, Malawi

Corresponding author: Rebekah Hinton. Rebekah.hinton@strath.ac.uk

Abstract

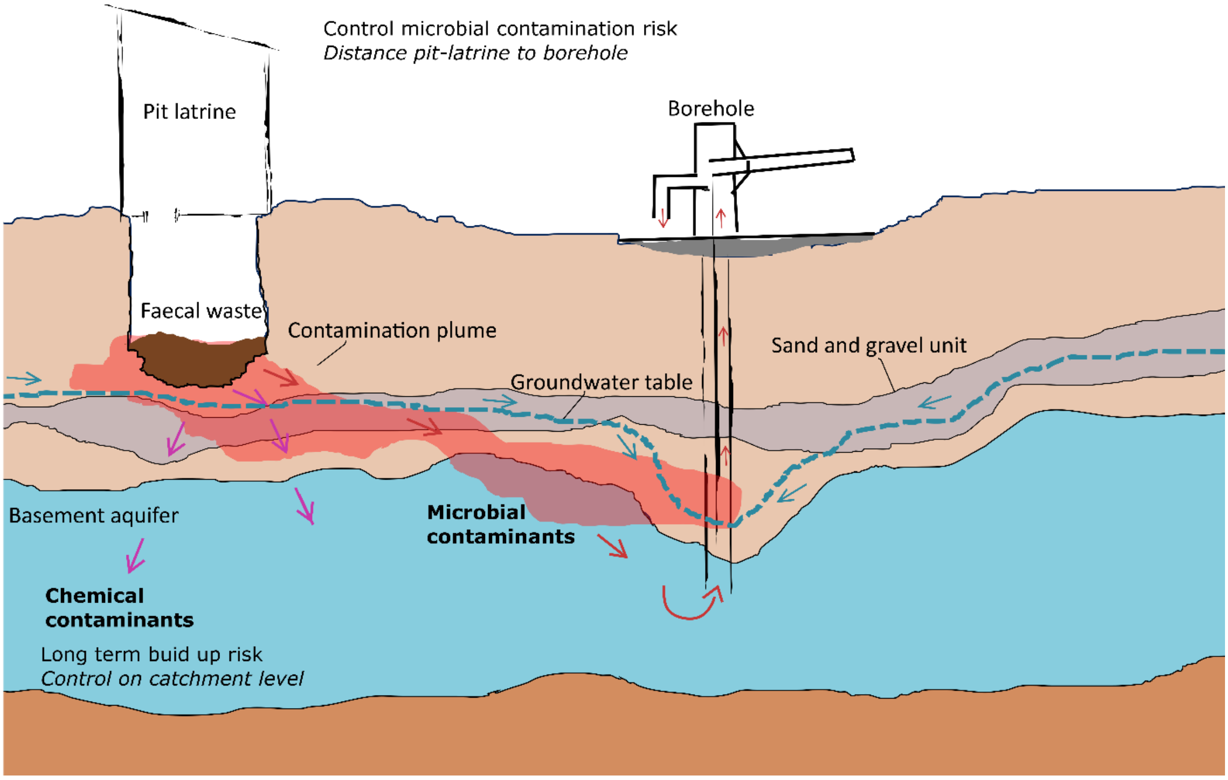
Pit-latrines are central to achieving UN Sustainable Development Goal 6 (SDG6) of ensuring "clean water and sanitation for all". Unless safely managed, pit-latrines result in groundwater contamination, which increases morbidity and mortality. Despite this, there have been no long-term spatial projections of future pit-latrine contamination risks. National survey data of over 100,000 water-points and 260,000 pit-latrines in Malawi was used to generate a novel, high-resolution model of pit-latrines from 2020-2070 under five population and three stakeholder informed sanitation policy scenarios.

The 'business as usual' model predicts a three-fold increase in the number of current water-points at risk of microbial pit-latrine contamination between 2020-2070, with a seven-fold increase in number at the highest risk of contamination. Current nitrogen loading into pit-latrines is comparable to national fertiliser application. The model predicts 8.2 mega-tonnes of faecal nitrogen will be disposed of into subsequently abandoned pit-latrines between 2020-2070. Guided intervention is necessary to prevent SDG6's push for sanitation undermining its goal of clean water.

Highlights

- Novel method to project groundwater contamination
- 5 population and 3 stakeholder informed sanitation policy scenarios for Malawi
- Business as usual model predicts a 3x increase in microbial borehole contamination
- Current nitrogen in pit-latrines comparable to national fertiliser in Malawi

Graphical abstract



Key Words

Groundwater, water quality, contamination, pit latrines, sustainable development

1 Introduction

The United Nations (UN) established the Sustainable Development Goal (SDG) 6 "clean water and sanitation for all" in 2015 (UN General Assembly, 2015). However, 3.5 billion people globally still lack safely managed sanitation (UNICEF & WHO, 2020). Improved sanitation is particularly important for reducing diarrhoeal disease, which causes 20% of deaths of children under-five in Eastern and Southern Africa Amouzou et al., 2016 . Pit-latrines provide low-cost, basic excretion management (Graham & Polizzotto, 2013; Hinton et al., 2023; Nakagiri et al., 2016) and are used by over 1.8 billion people (Gwenzi et al., 2023). They are critical for reducing Open Defecation (OD)(Gwenzi et al., 2023; Hinton et al., 2023) , still practised by 419 million people globally (UNICEF & WHO, 2020). Pit-latrine usage is likely to increase as we near the 2030 deadline for the SDG6.2 goal of 'sanitation for all'. (Gwenzi et al., 2023).

Despite the importance of pit-latrines to meet SDG6.2, the associated pathogen and chemical groundwater contamination may undermine efforts to meet SDG6.1(UN Water, 2023) on clean drinking water (Bhallamudi et al., 2019; Diaw et al., 2020; Graham & Polizzotto, 2013; Gwenzi et al., 2023; Mkandawire, 2008; Pritchard et al., n.d.; Rivett et al., 2022). Increased pit-latrine usage and continual construction to replace filled pit-latrines will result in growing numbers of abandoned latrines, and pose significant environmental and public health concerns (Gwenzi et al., 2023; Hinton et al., 2023). Malawi has a particularly high risk of drinking water contamination from pit-latrines due to the large proportion (85%) of the population using groundwater for drinking co-located with pit-latrines for sanitation (90%)(Graham and Polizzotto, 2013; Hinton et al., 2023). Globally, only Burundi has a similarly large proportion of the population reliant on groundwater for drinking and pit-latrine sanitation (Graham and Polizzotto, 2013). It is estimated that 60.2% of Malawi's population have *E.coli* in their source drinking water (NSO, 2021) indicating faecal water contamination, and 64.6% of the population have no water treatment (WHO, 2019). Where water treatment is available, the most common method is bleach chlorination used by 25.2% of the population (WHO, 2019), which has low efficiency for pathogen removal and is generally not recommended by the WHO(Nielsen et al., 2022; WHO, 2019). The implications for unsafe drinking water on public health was underscored in Malawi's deadliest cholera outbreak which occurred in 2022-2023, and was partially attributed to high levels of drinking water contamination (Sokemawu Freeman et al., 2024) .The high burden of pit-latrine contamination of drinking water makes Malawi a pertinent case-study to model contamination risk.

To manage the risk of microbial groundwater contamination from pit latrines, water-points should not be in close proximity to pit-latrines (Diaw et al., 2020; Dzwairo et al.,2006; Graham and Polizzotto, 2013; Reed, 2014; Sclar et al., 2016; Tillett, 2013; Verheyen et al., 2009). But there are discrepancies between guidelines for pit-latrine distance from water-points, ranging from 10m to 75m (Water Aid, 2013; Banerjee, 2011.; Blantyre Water Board, 2005; Chidavaenzi et al., 2000; Franceys, 1992; Sphere Association, 2018; Reed, 2014). Controlling the distances between water-points and pit-latrines provides an approximation of risk-management for water-point microbial contamination.

Nitrogen (as NO_3, NO_2 and NH_4) is also a contaminant of concern in groundwater (Ahmed et al., 2001.; Diaw et al., 2020; Puckett et al., 2011; Rahman et al., 2021). Nitrate can arise in groundwater from the oxidation of ammonia, a principal component of human excreta. High nitrate in water is an environmental and public health hazard(Ahmed et al., 2001; Puckett et al., 2011; Rahman et al., 2021), with nitrite being linked to methemoglobinemia in infants and stomach cancer in adults(Rahman et al., n.d.). Nitrate is relatively stable in aerobic conditions, presenting a risk of large distance transportation and long-term build-up of nitrate contaminants (Canter, 1996). Prevention of nitrate in groundwater is consequently critical to maintain water quality, even when sources of contamination are removed(Ahmed et al., 2001.; Rahman et al., 2021). Sources of nitrate contamination, such as pit latrines, pose a long-term risk to groundwater quality (Ahmed et al., 2001; Gwenzi et al., 2023; Puckett et al., 2011), and high nitrate concentrations in groundwater have been recorded in some regions of Malawi

(Mapoma et al., 2016; Missi and Atekwana, 2020; Pritchard et al., 2007, 2008). To manage nitrate contamination of groundwater from pit-latrines, nitrogen from human faeces must be prevented from entering groundwater, either by pit latrine emptying or creating physical barriers (lining) to the leaching of nitrogen(Ahmed et al., 2001). Management of risk requires monitoring of population density, type, and numbers of sanitation systems (Martínez-Santos et al., 2017; Ahmed et al., 2001; Diaw et al., 2020; Ndoziya et al., 2019.; Wright et al., 2013). Due to the potential long-distance transport of nitrates, contamination must be considered over larger scales, e.g., at catchment level (Canter, 1996).

Using high resolution population projections, we created a model of pit-latrine usage to predict groundwater contamination risk to 2070. The 5 Shared Socio-Economic Pathways (SSPs)(Riahi et al., 2017.) provided population growth predictions, accounting for demographics including age, sex, and education(KC and Lutz, n.d.). Combining SSP population projections with spatial population distribution models allowed spatially explicit population forecasts for various socioeconomic projections. Boke-Olen et al. (2017)(Boke-Olén et al., 2017.) combined SSP population projections with spatial distribution models to allow spatially explicit population forecasts for various socio-economic projections. They applied this model at a 30 arc-second resolution (approximately 1km at the equator) for an African population projection from 2000-2100. However, their results were not deemed to be at a sufficiently high resolution for analysis of the risks from pit-latrine usage as the previously discussed pit-latrine proximity is considered within 10-100m range. We apply a similar modelling approach at a greater 3 arc-second second resolution (approximately 100m at the equator)(Linard et al., 2012; Stevens et al., 2014; Worldpop, 2023) to produce higher-resolution and country-specific spatial population projections. We coupled the higher resolution population projections for Malawi with national survey data of over 100,000 water-points and 260,000 pit-latrines, to model pit-latrine use from 2020-2070, focusing on risks to groundwater in 2030 (end of the SDGs) (UN General Assembly, 2015.) and 2070 (end of Malawi's development plan 2063)(NPC, 2021).

We applied spatial variation in pit-latrine usage across administrative districts alongside estimates of the number of users sharing pit-latrines to predict pit-latrine users and density at 3 arc-second resolution (approximately 90m for Malawi). Together with policy makers, we co-developed 3 sanitation development scenarios with varying pit-latrine adoption (continued usage, increasing usage, and decreasing usage). Combining pit-latrine projections with contamination risk and faecal waste composition estimates from literature, enabled a novel time-series estimation of the risk for groundwater contamination. We present here the results for 'a business as usual' scenario of population demographics and pit-latrine adoption. Further scenarios are provided in the Supplementary materials.

This research presents a novel method for national identification and future prediction of vulnerable water-points at <100m resolution, enabling risk-basement investment of sanitation and water infrastructure. Though the case study is Malawi, the model can be applied to other countries and regions at similar risk of drinking water contamination. Model output will enable the Ministry of Water and Sanitation in Malawi to enact policy / management decisions for areas at the greatest risk of groundwater contamination from pit-latrines.

2 Methods

2.1 Study location

Malawi is a country in south-eastern Africa, Figure 1. Its population of over 20 million is mostly (84%) rural (NSO, 2021) . It is undergoing rapid demographic change with annual population growth of 2.6% (World Bank, 2023a) and urbanisation resulting in an expected 60% of the population classed as urban by 2060 (Commission and Malawi, n.d.). Malawi is one of the poorest countries in the world with a largely agro-based economy (employing over 80% of the population), making Malawi's economy particularly vulnerable to climatic shocks (World Bank, n.d.). Tropical cyclones and droughts have become more severe and frequent, causing substantial loss of life, economic impact, and environmental damage including to groundwater supplies (Rivett et al., 2022).

Groundwater provides the main source of drinking water for 85% of Malawi's population (Graham and Polizzotto, 2013), mainly accessed from boreholes/tube(NSO, 2021). Currently only 4.9% meet the requirement of SDG6.1.1, 'having improved drinking water source located on premises, free of E. coli and available when needed' (NSO, 2021; UN Water, 2023). Over 90% of the population use pit-latrines as their primary source of sanitation (Hinton et al., 2023; NSO, 2019; NSO, 2021; NSO & ICF, 2017).

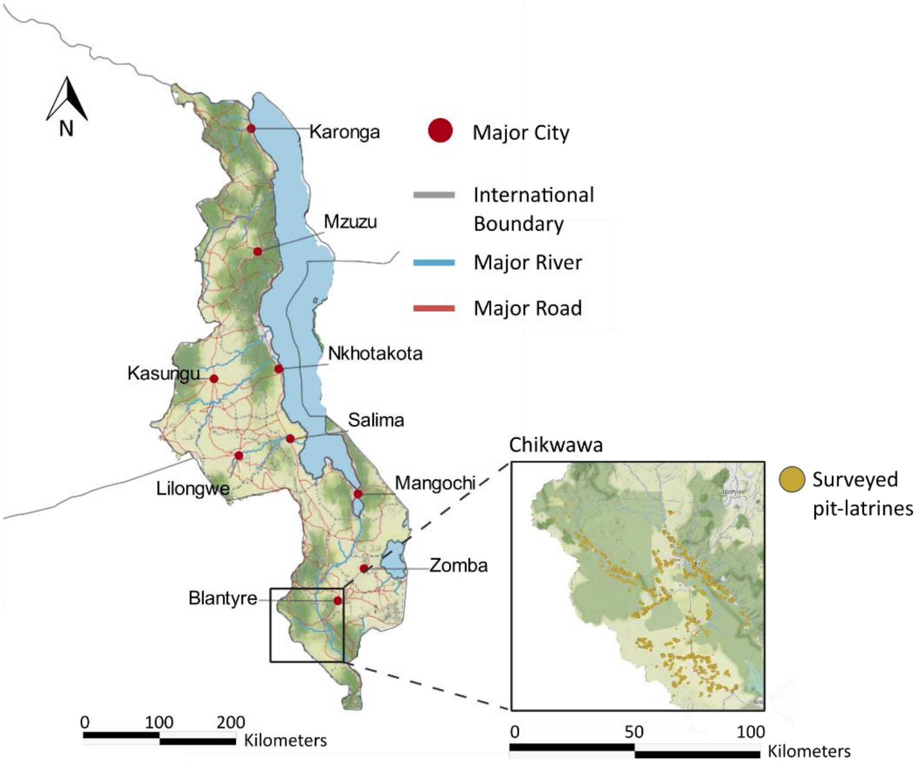


Figure 1: Map of case-study area (Malawi) showing major cities, rivers, and roads. The region of Chikwawa, where sanitation infrastructure is most comprehensively mapped, is highlighted with the locations of surveyed pit-latrines from the CJFWFP sanitation survey. Image made with QGIS using Stamen Terrain background.

2.2 Spatially explicit population estimation

Using a similar methodology to that outlined in Boke-Olen et al. (2017) and summarised in Figure 2, we generated a high resolution 3 arc-second resolution (approx. 90m in Malawi) spatially explicit gridded population projection from 2000 to 2070. The WorldPop 2000 unconstrained, 100m resolution population count for Malawi provided the initial spatial population distribution for the year 2000 at 3 arc-second resolution (Linard et al., 2012; Stevens et al., 2015; WorldPop., 2023). Locations of major roads in Malawi were accessed from the open-source Malawi Spatial Data Platform (MASDAP)(NSDC, 2023). Raster files of the distance to population centres and distance to roads in Malawi was calculated using the COGravity and distance functions respectively under the SDMTools packages(SDMTools, 2023) in R(R Core Team, 2023.). A unique spatial population grid was generated by combining the spatial population distribution, distance to roads, and the distance to population centres raster files, providing a population distribution weighted towards areas surrounding roads and population centres. The modified spatial population distribution was assigned into urban and rural areas based on the fraction of the cell classed as urban in 0.25-degree cells (approximately 39 km in Malawi) from Hurtt et al. (2011), Figure 2. Hurtt et al. (2011) provided urban fractions based on both socioeconomic and emissions scenarios. We assumed all scenarios follow a medium stabilisation emissions scenario, Representative Concentration Pathway (RCP) 6.0 (Fujino et al., 2006; Hijioka et al., 2008). In areas with a small proportion of cells classed as urban, there is a potential overconcentration of the population into urban cells. The urban population was distributed over a greater area by dividing the urban fraction outlined in Hurtt et al. (2011) by an 'Urban Fraction Smoothing Factor' (UFSF), ranging from 0-1.

Multiple socioeconomic scenarios of population growth and urbanisation were considered using the 5 shared socioeconomic pathway (SSP) scenarios that project population and urbanisation levels under hypothetical socioeconomic scenarios (Riahi et al., 2017). The SSP pathways were chosen due to their well-established scenario building and diverse representation of both population and economic change, representing not only population growth but also urbanisation. SSP1 and SSP5 are low population growth scenarios with high urbanisation. SSP3 and SSP4 are high population growth scenarios with low and high urbanisation respectively, and SSP2 represents a 'middle of the road' scenario with moderate population growth and urbanisation (Riahi et al., 2017).

The projected urban/rural population for a given SSP scenario was distributed between respective urban and rural cells based on weighted population value of the cells. This was repeated iteratively for subsequent years to produce population projections. The approach is summarised in Figure 2.

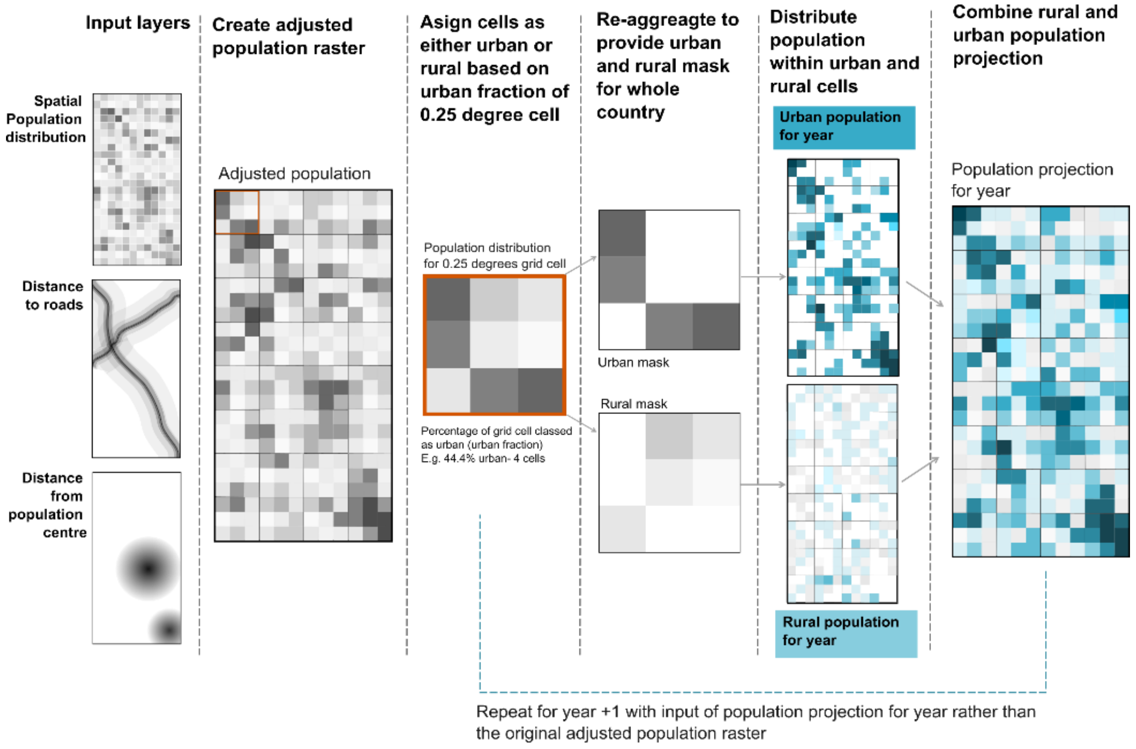


Figure 2: Diagrammatic overview of population projection methods. Methodology for population projections based on Boke-Olen et al., (2017). Input layers are the initial 100m Worldpop spatial population distribution for the year 2000(Linard et al., 2012; WorldPop.,

2023) alongside raster files of the distance to roads and distance to population centres generated using the R SDMTools package(R Core Team, 2023; SDMTools, 2023). These are combined to create a weighted population raster for the year 2000. The weighted population raster is used to produce urban and rural masks into which the urban and rural population is distributed based on the adjusted Hurtt et al., (2011) urban fraction. The process is repeated iteratively with the previous year spatial population distribution used as input rather than the adjusted, weighted population raster.

2.3 Validation of population estimates

To validate our population estimates, the projected population distribution for the year 2020 (20 years of modelled distribution) was compared to the WorldPop 2020 population distribution for 3 arc-second and 30 arc-second resolution(Linard et al., 2012.; WorldPop, 2023). The results of different Urban Fraction Smoothing Factors (UFSF) were compared to WorldPop 2020 spatial population distributions at 100m and 1km resolution. UN-adjusted and non-adjusted were used as reference population distributions (Linard et al., 2012; WorldPop, 2023). Results are summarised in Supplementary materials Table 1 and 2. The Root Mean Squared Error (RMSE)(Chen et al., 2020; Yin et al., 2021) of the difference between the projected population raster and reference population raster was calculated using equation (1).

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(P_n - R_n)^2} \qquad (1)$$

Where N is the number of cells within the raster file, n is the given cell investigated, P is the projected raster and R is the reference raster.

As the RMSE value can be strongly influenced by individual outliers (Yin et al., 2021.), we calculated the percentage of cells in which the projected population differed from the reference WorldPop raster (Linard et al., 2012.; WorldPop, 2023.) by more than 1, 10 or 100 people for 3 and 30 arc-second resolutions. For comparison, the RMSE value for Boke-Olen et al., (2017)(year 2020, scenario SSP2 RCP6) 30-arc second resolution was compared to WorldPop 2020 (UN-adjusted 1km resolution) population(Linard et al., 2012; WorldPop, 2023).

To compare available gridded population databases for Malawi, the total population count for 2020 was calculated for WorldPop datasets (UN-adjusted and non-adjusted and at 100m and 1km resolution)(Linard et al., 2012; WorldPop, 2023), Landscan(ORNL, 2023), Boke-Olen et al., (2017) projected populations (SSP2 RCP6)(Boke-Olén et al., 2017), and the model presented here. The percentage error from the World Bank Malawi 2020 population estimation was calculated (World Bank, 2023b).

2.4 Sanitation policy scenarios

The rural and urban population distributions were divided into administrative districts, boundaries available from MASDAP(NSDC, 2023). The Demographic Health Survey (DHS) 2015-2016 data was used to indicate the level of pit-latrine adoption for rural and urban populations each in district (NSO & ICF, 2017). The DHS 2015-2016 being the most recent survey providing a breakdown of the sanitation facility usage in urban and rural contexts, alongside district level data of 'improved' and 'unimproved' sanitation access (NSO & ICF, 2017). For each district, the ratio of improved/ unimproved sanitation use, for both urban and rural contexts, was used to scale the national percentage of the population utilising each type of sanitary facility. The percentage of the population in each district (rural and urban) using pit-latrines was multiplied by the spatial population distribution to estimate the distribution of pit-latrine users, see Figure 3.

Three stakeholder informed sanitation policy scenarios were proposed to account for high uncertainty in future sanitation infrastructure development. Scenario A assumed that from 2020-2070, the percentage of the population using pit-latrines remains the same as in 2015 using the pit-latrine usage data from the DHS 2015-16 survey (NSO & ICF, 2017). This is most similar to the current status of sanitation and is consistent with the Government of Malawi's current sanitation development plans in which there are no plans to deviate from pit-latrines as the main sanitation provision (NPC, 2021).

Scenario B assumed that the percentage of the urban and rural population using pit-latrines follows a linear model from the 2015-16 district pit-latrine usage (NSO & ICF, 2017.) to a 2070 forecast. The 2070 forecast was estimated by modelling the percentage of the population that will be using flush toilets (to septic tanks or sewerage systems) in 2070, applying a simple linear regression model using the lm() function in the Stats package in R(R Core Team, 2023.) and assuming the remaining population will be using pit-latrines. The model assumed that Malawi would achieve its target of ending OD, largely through pit-latrine promotion. This model is consistent with modelled projections of increasing the rate of pit-latrine to enable Malawi to end OD by 2070 (Hinton et al., 2023). Whilst each district has a different pattern of change in the number of pit-latrine users, this scenario had a national increase in pit-latrine use.

Scenario C assumed an increase in the provision of flush toilets to septic tanks and sewers from 2015 to 2070, modelled on the change in the percentage of the population using flush toilets observed in Botswana from 2001 to 2011(Statistics Botswana, 2015; Statistics Office, 2005). Botswana was chosen as a case-study of another Southern African Development Community (SADC) member state that achieved an ambitious shift from pit latrine promotion-focused sanitation to central provision of piped sewerage systems, following the declaration of the International Drinking Water and Sanitation Decade from 1981 (Bolaane and Ikgopoleng, 2011). Botswana's sanitation transition is considered an ambitious but achievable sanitation policy, providing a realistic scenario of a deliberate shift away from pit-latrine dependency. From 1981 to 2011, the percentage of Botswanan population using their own flush toilet increased from 8.6% to 25.2% (Statistics Botswana, 2015; Statistics Office, 2005). The linear trend of flush latrine adoption in Botswana was applied to the Malawi case study by adjusting the intercepts to the percentage of flush latrine usage in Malawi according to the DHS 2015-16 survey (NSO & ICF, 2017) for rural and urban contexts. The remaining population in 2070 was assumed to use pit-latrines. The model assumes an overall reduction in the percentage of the population using pit-latrines through promotion of flush toilets. The model assumes Malawi ends OD by 2070.

For Scenarios B and C, annual estimates of pit-latrine use are made for each district from a linear model (lm() function, R Stats package (R Core Team, 2023.)) of the district pit-latrine in 2015/16 levels (NSO & ICF, 2017) to 2070 projections. Scenarios B and C are summarised in Supplementary materials Figure 2.

2.5 Cumulative faecal loading

Spatial estimates of pit-latrine users for different years, SSP and sanitation policy scenarios were calculated as the product of the spatially explicit population and pit-latrine usage estimations. To evaluate spatial differences in latrine user density, the estimated number of latrine users was subdivided into river sub catchments, water resource units (WRUs) (Kalin et al., 2022). Nitrate contamination is considered on a catchment scale to account for long-distance nitrate transportation which is common in groundwater (Canter, 2019).

The quantity of excreta loaded into each WRU was calculated to identify WRUs at risk of groundwater contamination, with a focus on nitrogenous contamination. To calculate the volume of faecal waste the number of latrine users was multiplied by the estimated volume of faecal matter per capita per year using literature estimates. The cumulative loading of faecal waste was calculated by summing the volume of excreta per year produced by users from 2020 to 2070 for each WRU. Ranges in excreta volume and composition were used to account for uncertainty. For the volume of excreta produced, an average volume of extra per individual was used as 270 L/year, based on an extensive study of pit-latrine loading in Kampala, Uganda (Strande et al., 2018). To calculate the range of annual excreta values an upper estimate of 1000L per capita and a lower estimate of 100L per capita were applied (Strande et al., 2014, 2018, UNEP, 2023).

The number of latrine users was also multiplied by the estimated chemical composition of faecal waste to calculate the total volume of chemicals in the waste. The average, upper, and lower estimates of the chemical composition of faecal waste per capita per day were taken from literature (Strauss et al., 2003; Del Porto & Steinfeld, 1999; G.T.Z. Ecosan, 2000; Hansen and Tjell, 1979; Schouw et al., 2002; West et al., 2009). An average estimate of 12.5g/ppd Nitrogen content was taken from estimates used in compositing and EcoSan toilet designs (Del Porto & Steinfeld, 1999; G.T.Z. Ecosan, 2000.). The upper estimate of 19g N/ppd was taken based on a study of adult excreta in Denmark, averaged 16g/ppd (range 12-19g)(Hansen and Tjell, 1979). The lower estimate of 7.6g/ ppd was taken based on a study of adults and children in Thailand, averaged 7.75g/ppd (range 7.6-7.9g)(Schouw et al., 2002). The average phosphorus content of waste was taken as 2g/ppd (Strauss et al., 2003). A lower estimate of 1.5g/ppd was taken from latrine design literature (Del Porto & Steinfeld, 1999; G.T.Z. Ecosan, 2000)). An upper estimate of 3.7g/ppd was based on adult excreta in Denmark (range 1.8g-3.7g)(Hansen and Tjell, 1979). For potassium, an average estimate of 3g/ppd was applied (Strauss et al., 2003). A lower estimate of 1.8g/ppd was taken from a study of adult and child excreta, Thailand (range 1.8-2.7g)(Schouw et al., 2002). An upper estimate of 3.5g/ppd was taken (Del Porto & Steinfeld, 1999; G.T.Z. Ecosan, 2000.). For carbon content, an average carbon estimate was taken as 17.9g/ppd in human excreta (West et al., 2009). A lower estimate of 14g was applied based a study of adult and child excreta in Thailand (range 14-26g)(Schouw et al., 2002). An upper estimate of 30g/ppd was from literature on latrine design and compositing (Strauss et al., 2003; Del Porto & Steinfeld, 1999; G.T.Z. Ecosan, 2000). The cumulative faecal load was divided by the area of the WRU to estimate the spatial density of faecal waste loading, Figure 3.

2.6 Latrine density

An extensive survey of pit-latrines, waste sites and water points in Malawi was conducted by the Government of Malawi through the Climate Justice Fund Water Futures Programme (CJFWFP) from 2012 to 2020, using semi-structured interviews of stakeholders at each facility. Trained staff delivered interviews in both Chichewa and English and provided the location of each site with a photograph of the facility. Responses were hosted on the data-platform mWater (mWater, 2023). Quality control was provided by the University of Strathclyde and all data collected was in line with the Government of Malawi ethics and was agreed with each participant. Data cleaning involved the removal of incomplete and duplicate responses resulting in 264,514 points for analysis.

The most comprehensively mapped district of Malawi was Chikwawa (Figure 1), with most surveys conducted in 2017. Case studies from the district of Chikwawa were used to approximate population per pit-latrine. The district of Chikwawa was divided into rural and urban based on the 2017 population; 3 urban and 3 rural regions were selected and the number of surveyed pit-latrines within case-study area was summed. The number of pit-latrines was divided by the estimated population using pit-latrines for each area calculated from the WorldPop 100m population estimate for the year 2017 (Linard et al., 2012; WorldPop, 2023). The urban and rural case studies were averaged to estimate the number of latrine users per latrine in urban and rural contexts. To estimate the number of pit-latrines, the number of pit-latrine users was divided by the number of users per pit-latrine for urban and rural cases.

To identify water-point contamination risk from pit-latrines, cells were classified according to the number of pit-latrines in each 3 arc-second grid. The equivalent distance a pit-latrine would be from a water-point in a 3 arc-second cell for given latrine density was estimated to provide estimate the associated risk. The number of latrines likely to be within a given radius of a waterpoint was estimated from the density of latrines using equation (2):

$$N \leq \frac{log(0.05)}{log(1-(\frac{\pi r^2}{l^2}))} \tag{2}$$

Where N is the number of pit-latrines within a grid cell of length, l, necessary to have a 95% probability that at least one latrine will be within a radius r of a centrally located water-point.

Estimating the radius from a central water-point enabled comparison of latrine density estimates to the wider body of literature relating the water-point contamination risk to the distance to a pit-latrine(Water Aid, 2013.; Banerjee, 2011.; Blantyre Water Board, 2005.; Chidavaenzi et al., 2000.; Dzwairo et al., 2006.; Franceys, 1992; Graham and Polizzotto, 2013; Sphere Association, 2018.; Reed, 2014; Sclar et al., 2016.; Tillett, 2013; Verheyen et al., 2009.).

The CJFWFP water-point survey geolocated 126,994 improved and unimproved water points across Malawi, enabling identification of water-points at high risk of contamination (Kalin et al., 2019). 'Vulnerable water-points' were defined as boreholes, tube-wells or dug wells (both protected and unprotected) that were functional and in-use (but not primarily for agricultural, or livestock). Point locations of vulnerable water-points were aggregated into pixels, at 3 arc-second resolution, to generate a binary raster of vulnerable water-point presence/absence. Latrine density was considered in cells containing a 'vulnerable' water-point. Cells containing a vulnerable water-point in which the density of latrines exceeded a threshold density were identified, Figure 3.

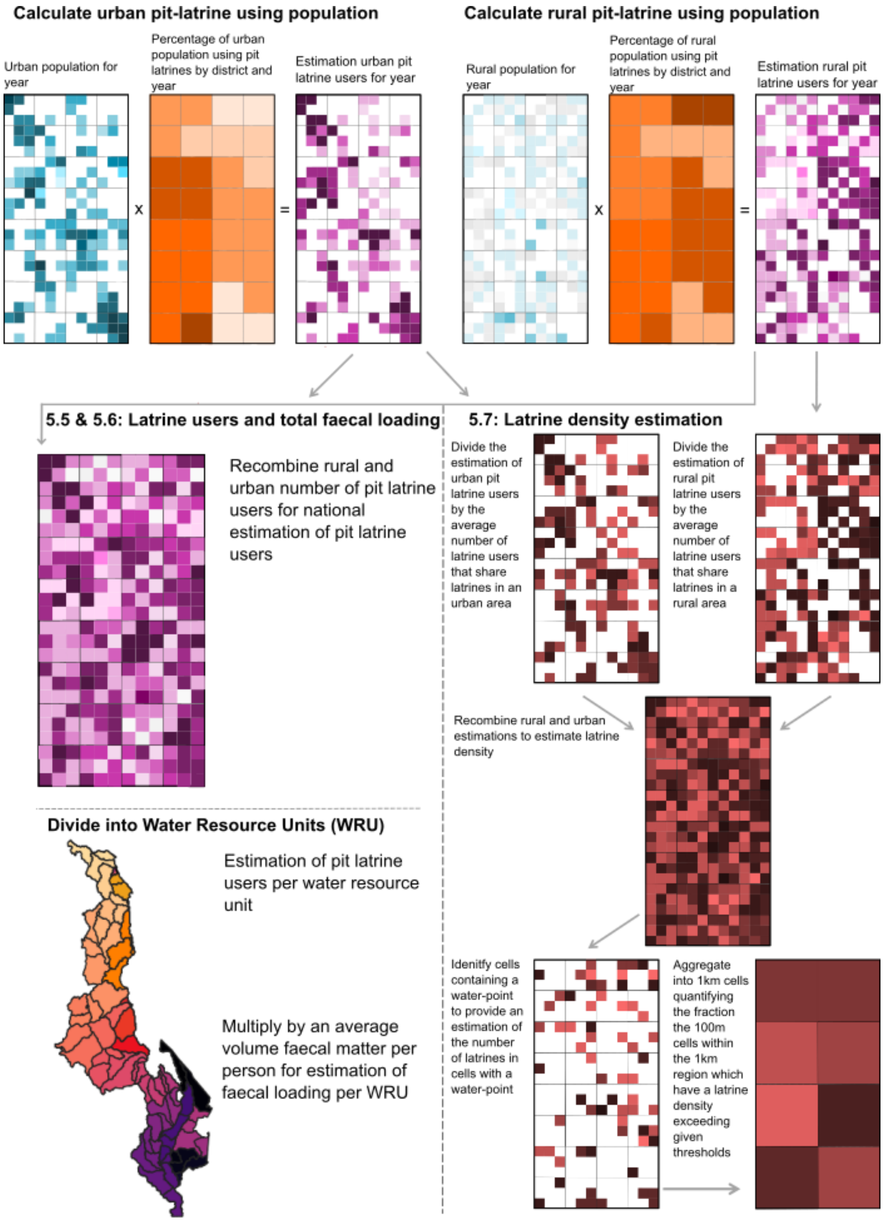


Figure 3: Diagrammatic overview of methods used in estimation of pit-latrine users and density. Blue grid cells represent population density, orange represents the percentage of people in a given district that use pit-latrines, purple grid cells represent latrine users and red cells represent latrine density. Darker colours relate to higher densities of population, latrine users and pit-latrines.

To account for spatial variation and uncertainty in population distribution and the locations of sanitation and water facilities, 3 arc-second grids were aggregated. The percentage of 3 arc-second cells within a 30 arc-second grid containing a vulnerable water-point with latrine densities exceeding the latrine thresholds was summarised under multiple scenarios.

CJFWFP water-point data (Kalin et al., 2019) identified whether water-points were within 100m of a latrine (Government of Malawi recommended spacing (Blantyre Water Board, 2005)), and was used for model validation. The percentage of vulnerable water-points within 100m of a latrine was calculated. Equation (3) enabled comparison of the percentage of cases in which a water-point was within 100m of a latrine with the percentage of cases in which a water-point was found within the same 3 arc-second grid cell as a latrine:

$$P_g = \frac{P_r l^2}{\pi r^2} \tag{3}$$

Where P_g is the percentage of water-points with a pit-latrine within the same grid cell of length l, and P_r is the percentage of water-points with a pit-latrine within a radius, r (here, r=100 m). This assumes an even distribution of latrines within the cell and a centrally located water-point.

Further verification was achieved through visual inspection comparing the locations of pit-latrines from the CJFWFP sanitation survey to the modelled predicted latrine density for 2020, an example is shown in Supplementary materials Figure 5.

3 Results

3.1 Latrine density

A dataset of 126,994 water-points, surveyed from 2012-2020 by the Government of Malawi Ministry of Water and Sanitation staff under the Climate Justice Fund Water Futures Programme (CJFWFP)(Kalin et al., 2019), identified 49,000 ‘vulnerable water-points’ (functional and in-use boreholes, tube-wells, or dug wells not used primarily for livestock or agriculture). Boreholes or tube wells were the most common vulnerable water-points (41,000), followed by protected dug wells (7,700) and unprotected dug wells (310). Of the vulnerable water-points, 23,100 reported a pit-latrine within 100m (58.6% of the 39,500 water-points for which a response was listed). This is equivalent to 15.1% of vulnerable water-points having a pit-latrine within the same 3 arc-second grid cell, calculated from equation (3).

The associated risk to water-points of given pit-latrine densities, calculated using equation (2), is summarised in Table 1. The number of cells surpassing thresholds of pit-latrine density is shown in Figure 4 with data summarised in Supplementary materials Tables 4 and 5. We estimate that in 2020, 11.5% of vulnerable water-points had at least one pit-latrine within the same 3 arc-second grid cell. This increases to 18.0% by 2030 and 33.6% by 2070.

Figure 5 shows a spatial representation of at-risk cells. Areas at highest risk of faecal water contamination are concentrated generally around urban centres. There is an increase in both the number of water-points at risk of faecal water contamination and the severity of risk to water-points. There is a 720% increase in the number of vulnerable current water-points within a 3-arc second cell containing 30 or more pit-latrines from 2020-2070.

Table 1: Conceptualised water-point contamination risk at given pit-latrine densities. Density of pit-latrines within a 3 arc-second grid cells (ca 90m in Malawi) and associated estimated distance of pit-latrines to a centrally located water-points, calculated by equation (2). The associated risk of a pit-latrine being located at the given proximity to the water-point is conceptualised.

Number of pit-latrines in 3 arc-second grid cell	Equivalent latrine radius estimate (>95% Confidence)	Risk level	Guideline exceeded
1 latrine	At least 1 latrine within 50m	Low risk	WaterAid **50m** distance(Aid, n.d.)
3 latrines	At least 1 latrine within 40m	Low-moderate risk	WEDC Loughborough University **40m** distance(Reed; Bob, 2014)
10 latrines	At least 1 latrine within 26m	Moderate risk	Sphere Project **30m** distance(Project, n.d.)
30 latrines	At least 1 latrine within 16m	Moderate-high risk	Chidavaenzi et al., (2000)(Chidavaenzi et al., n.d.)
50 latrines	At least 1 latrine within 12m	High risk	WHO **15m** distance(Franceys, 1992)
100 latrines	At least 1 latrine within	Very high risk	Banerjee

	9m		(2011) **10m** distance(Banerjee, n.d.)

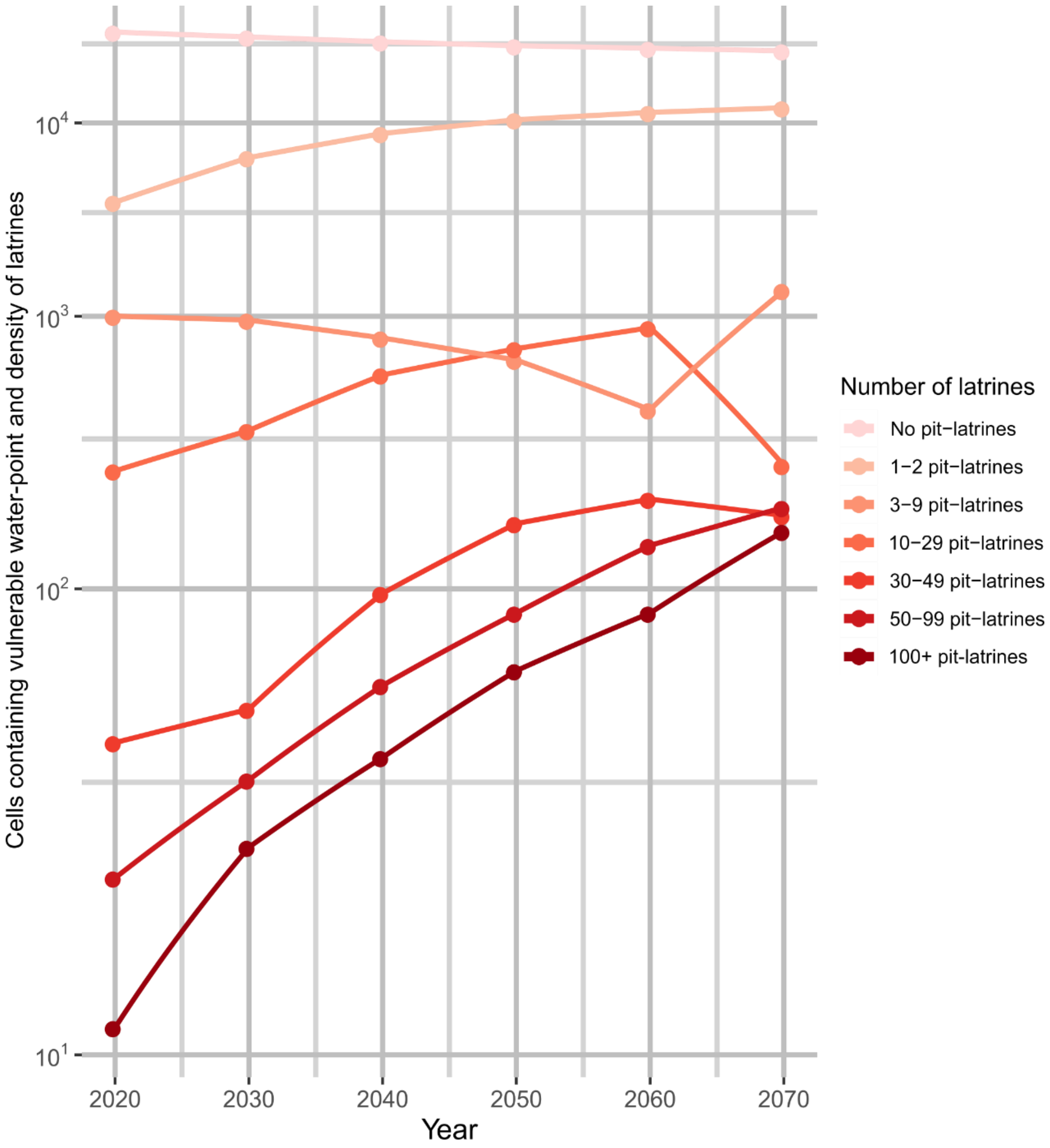


Figure 4: Change in number of vulnerable water-points at risk of contamination from 2020-2070. Number of 3 arc- second grid cells containing a vulnerable water-point and given densities of pit-latrines between 2020 and 2070 under SSP scenario 2, sanitation policy scenario A.

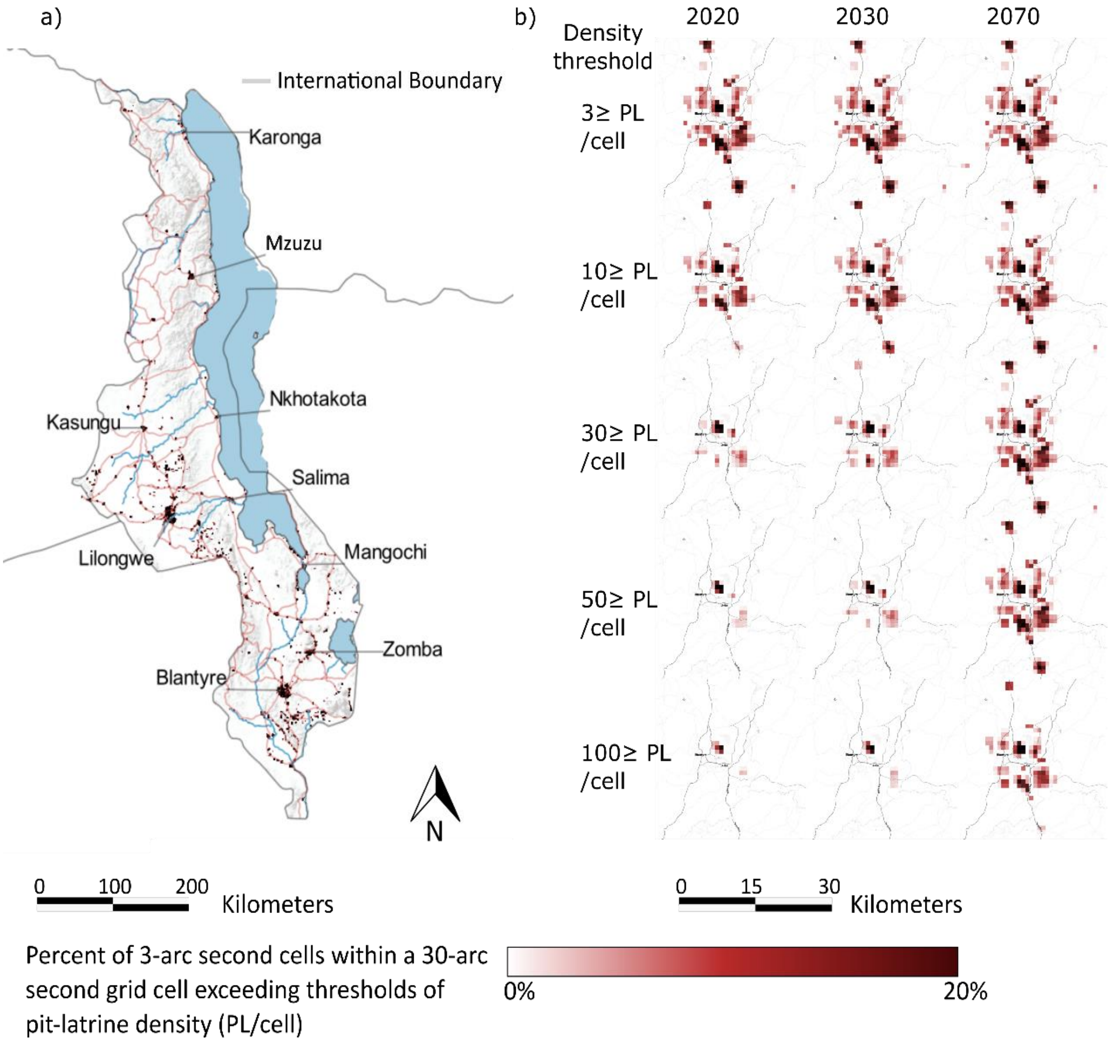


Figure 5: Spatial distribution of areas at greatest risk of faecal water contamination.

a) The fraction of 3 arc-second grid cells (approximately 90m) within 30 arc-second grid cells (approximately 9km) containing a vulnerable water-point and 3 or more predicted pit-latrines for the year 2070 under SSP2, sanitation policy scenario A. Darker cells indicate a higher fraction of cells within 30 arc-second grid cells containing both a vulnerable water-point and 3 or more pit-latrines. Image made with QGIS using Esri Terrain background.

b) Proportion of 3 arc-second grid cells within 30 arc-second grid cells containing vulnerable waterpoints and pit-latrine densities over given thresholds in Blantyre City Malawi for the years 2020, 2030, and 2070 under SSP2 scenario A. Image made with QGIS using Stamen Toner Light background.

3.2 Cumulative faecal loading

The cumulative national loading of faecal sludge components is summarised in Table 2. Upper and lower estimates are given based on upper and lower estimates of faecal loading and faecal waste composition. Under business-as-usual projections, 8.2 mega-tonnes of nitrogen in faecal waste will be loaded into pit-latrines from 2020-2070 in Malawi. Current annual volumes of nitrogen loading are comparable to the nitrogen in current national fertiliser application(Ritchie, 2020). Figure 6 shows the cumulative quantity of faecal sludge, per sub-catchment Water Resource Unit (WRU) from 2020-2070. Comparison of the faecal loading for WRUs by 2070 under the 5 SSP and 3 sanitation policy scenarios are summarised in Supplementary materials Figure 4.

Table 2: Cumulative faecal waste across Malawi (giga-litres) and constituent chemicals (mega-tonnes). Loading from 2020 to 2070 under SSP scenario 2, sanitation policy scenario A (no change). Cumulative quantity of faecal waste is estimated from projected number of pit-latrine users and estimates of faecal make up.

	2020-2030	2020-2040	2020-2050	2060	2070
Cumulative volume faecal loading / giga-litres	51 (19-190)	130 (48-480)	230 (85-850)	340 (130-1300)	480 (180-1800)
Cumulative mass of Nitrogen / mega-tonnes	0.87 (0.53-1.3)	2.2 (1.3-3.3)	3.8 (2.3-5.8)	5.7 (3.5-8.7)	8.2 (5.0-12)
Cumulative mass of Phosphorous / mega-tonnes	0.13 (0.10-0.25)	0.44 (0.33-0.81)	0.73 (0.55-1.4)	1.0 (0.77-1.9)	1.3 (1.0-2.5)
Cumulative mass of Potassium / mega-tonnes	0.21 (0.12-0.24)	0.53 (0.32 -0.62)	0.94 (0.6-1.1)	1.37 (0.82-1.6)	2.0 (1.8-2.3)
Cumulative mass of Organic Carbon / mega-tonnes	1.3 (0.98-2.1)	3.2 (2.5-5.3)	5.5 (4.3-9.2)	8.4 (6.5-14)	12 (9.3-20)

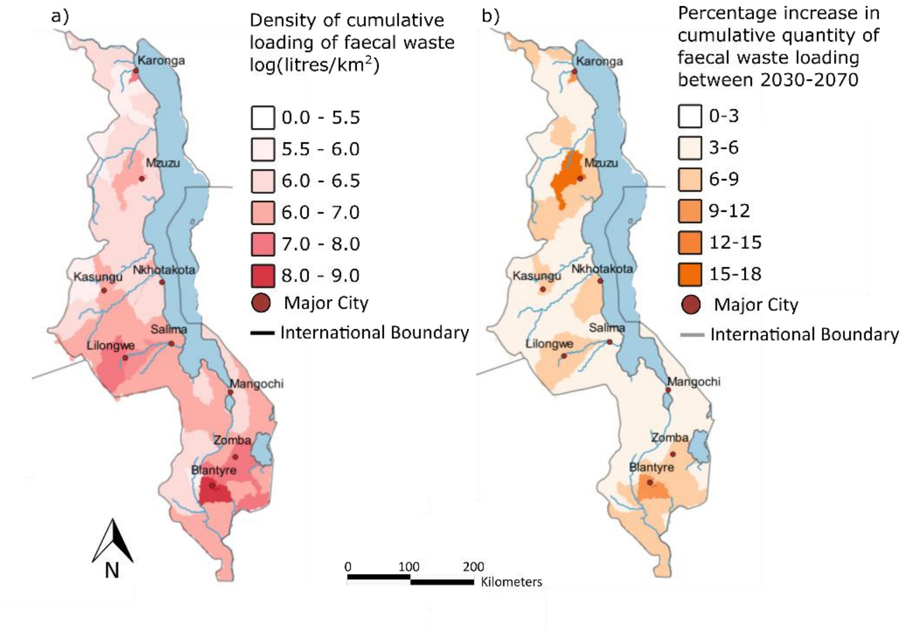


Figure 6: Spatial distribution of areas at greatest risk of chemical water-contamination from cumulative faecal waste loading. A) Density of cumulative loading of faecal sludge from 2020 to 2070 per km^2 in each WRU across Malawi. WRUs surrounding cities Blantyre, Lilongwe and Karonga have the greatest faecal sludge loading. B) Percentage increase of cumulative loading of faecal sludge (litres/ km^2), logarithmic scale, between 2030 and 2070. The WRUs around Blantyre, Lilongwe and Karonga have a significant increase in faecal loading density between 2030-2070, but WRU 7D around Mzuzu has a particularly high projected increase in faecal sludge density. Image made with QGIS.

3.3 Model verification and assumptions

Population projections (with model run from 2000-2020) were compared to gridded population datasets for 2020. Boke-Olen's et al.'s (2017)(Boke-Olen et al., 2017) spatially explicit population estimation for 2020 SSP2-RCP6 had a Root Mean Square Error (RMSE) of 933 when compared to WorldPop 2020 UN adjusted data at 1km resolution(Linard et al., 2012; WorldPop, 2023). Our model has a RMSE of 4.5 when compared to WorldPop 2020 UN adjusted data at 1km resolution. We applied an urban smoothing factor of 0.4 to the Hurtt et al. (2011)(Hurtt, et al., 2011) estimation to prevent overconcentration of the urban population. Our modelled population projections at 30 arc-second resolution for the year 2020 are highly accurate and show a difference from WorldPop 2020 1km spatial population distribution of 3.4% of cells differing by 1 person or more, 0.2% by 10 people or more, and 0.01% by 100 people or more (Supplementary materials Table S1). Our model therefore has a -1.64% total population estimate error compared to World Bank Malawi 2020 population (World Bank, 2023a). This is lower than Landscan (ORNL, 2023.), and Boke-Olen et al. (2017) total Malawi population predictions for 2020 (1km resolution) which have +49.6%, and +8.32% errors respectively (Supplementary materials Table S2).

We propose three sanitation policy scenarios, focused on pit-latrine usage, summarised in Supplementary materials Figures S1 and S2. Scenario A assumes the percent of the population using pit-latrines remains the same as the 2015/16 Demographic and Health Survey (DHS) estimate; 85.3% of the urban and 92.8% of the rural population(Zomba and Malawi, n.d.). Sanitation policy Scenario B assumes that, if the current rate of flush toilet acquisition continues and the remaining population use pit-latrines, 84.7% of the urban and 97.1% in rural population would use pit-latrines by 2070. Scenario C assumes that if Malawi follows the trend of flush-latrine adoption in Botswana(Statistics Botswana, 2015; Statistics Office, 2005.), 54.4% of the urban and 68.4% of the rural population would use pit-latrines in 2070. Spatial variation in pit-latrine use is summarised in Supplementary materials Figure S3.

Following data cleaning, we analysed 265,000 sanitation facilities (from the CJFWFP national sanitation survey completed in 2020). The number of users per latrine for urban and rural case-studies was calculated from the sanitation data. We estimated 9.4 and 12.7 people per latrine in urban and rural cases respectively, Supplementary materials Table 3.

4 Discussion

4.1 The burden of pit-latrines on safe drinking water

Open defecation (OD) in Malawi has fallen from 27.7% in 1992 to 5.9% in 2018 (NSO & Macro International, 1994; NSO &ICF, 2017) largely due to the promotion of pit-latrines. Given their short life (often filling in 2 to 3 years), continual pit-latrine construction is necessary not only to reduce the level of OD, but also to respond to population growth and to replace filled or unstable latrines (Hinton et al., 2023). Such unfettered growth in the number of pit-latrines is a potential crisis for groundwater quality.

Our model accounts for multiple population growth and urbanisation scenarios using the 5 shared socioeconomic pathways (SSPs)(KC and Lutz, 2017.; Riahi et al., 2017), hypothetical scenarios of global socioeconomic change. Each SSP population scenario is investigated alongside three sanitation policy scenarios (current sanitation policy, ending OD by pit-latrine promotion, or ending OD by expansion of piped sanitation). Whilst some sanitation policy scenarios are more probable under specific SSP scenarios, for example SSP1 'sustainability' is likely to be accompanied by more sustainable sanitation policy whilst SSP3 and 4 'fragmentation and inequality 'would likely have scenarios with higher pit-latrine dependency, all policy and SSP scenarios are considered to inform stakeholder decision making. All modelled scenarios, incorporating population and sanitation policy scenarios, predict increasing risks to groundwater posed by pit-latrines. The results here use SSP2, a 'middle of the road' model of socioeconomic growth and urbanisation(KC and Lutz, 2017; Riahi et al., 2017) and a sanitation policy scenario that assumes a constant proportion of the population using the sanitation systems as in 2015/16 (NSO &ICF, 2017) other SSP and sanitation policy scenarios are summarised in the Supplementary materials.

Microbial contamination is a significant problem in Malawi (Mkandawire, 2008; Pritchard et al., 2007, 2008; Rivett et al., 2022). Over 60% of the population's drinking water sources have measurable *E.coli* and 16.5% has over 100 faecal coliforms / 100ml (NSO, 2021), surpassing the Malawi's current rural water quality target of 50 Total Coliforms/100ml for untreated water (Mkandawire, 2008; Pritchard et al., 2008). The high-resolution model enables consideration of short-term movement of pathogens from pit-latrines to water-points (boreholes, tube-wells or dug-wells). Here, 3 arc-second grid cells containing both a vulnerable water-point and a pit-latrine are identified as presenting a risk of contamination. We predict that by 2030 (end of the SDG period) 18.0% of vulnerable water-points will have a pit-latrine within 50m (a cell containing a vulnerable water-points and 1 or more pit-latrines), exceeding both Government and NGO guidelines (Water Aid, 2013; Blantyre Water Board, 2005). This increases to 33.6% by 2070. Furthermore, we project an increase in the number of water-points at risk from contamination and the severity of risk. From 2020, there is a 720% increase in vulnerable-waterpoints considered at high contamination risk (within the same 3 arc-second grid cell 30 or more pit-latrines).

Literature and survey estimates of pit-latrine density support the results. Modelled water-point vulnerability was validated using results from the national 2012 to 2020 CJFWFP survey of over 100,000 water-points (Kalin et al., 2019). The number of surveyed water-points with a pit-latrine within a 3 arc-second grid cell was 15.1%. Our model is in good agreement, estimating that 11.5% of 3 arc-second grid cells contained both a pit-latrine and water-point in 2020. The difference is at least to some extent due to the model not accounting for grid cells containing multiple water-points. A case-study of Blantyre, Chiradzulu and Mulanje found that 25% of shallow wells were within 40m of pit-latrines or waste pits (Pritchard et al., 2007), resulting in a higher estimate than here; it should be noted this was not a country-wide analysis.

The cumulative faecal load in pit-latrines across Malawi from 2020 to 2070 projects a total of 482 giga-litres of faecal matter loaded into pit-latrines, containing approximately 8.2 mega-tonnes of nitrogen, 1.0 mega-tonnes of phosphorous, 2.3 mega-tonnes of potassium, and 19.6 mega-tonnes of organic carbon. From 2020 to 2030 alone there is an additional 51.2 giga-litres of faecal waste in the ground containing 0.9, 0.1 and 0.2 mega-tonnes of nitrogen, phosphorous, and potassium respectively. For reference, in 2019, 0.23 mega-tonnes of fertiliser containing 0.08 tonnes of nitrogen, 0.02 mega-tonnes of phosphorous and 0.02 mega-tonnes of potassium were applied in Malawi (Ritchie, 2020). The mass nutrients in faecal waste within pit-latrines is therefore comparable with that of fertiliser applied in Malawi. Whilst much of the waste will be broken down, absorbed, or microbially metabolised, it presents a risk of build-up within groundwater (Puckett et al., 2011; Zingoni et al., 2005), with significant public health, environmental, and policy implications.

The concentration of faecal sludge and associated risk of contamination for each Water Resource Unit (WRU) is the cumulative volume of faecal waste per WRU divided by the area of the WRU. WRUs surrounding key cities (WRU 1B, 1E2, 1C and 14A around Blantyre and WRU 4E and 4D surrounding Lilongwe) have the highest projected cumulative faecal sludge loading density from 2020 to 2070. WRU 17A (northern Malawi) has a low faecal loading of 2.9 giga-litres, however as it is concentrated within a small sub-catchment, the result is a high density of faecal waste. Policy and management interventions may require a change in sanitation infrastructure, focusing on waste removal, waste processing, or alternative water provision through piped water supplies and water source protection zones, to manage contamination risk (Zingoni et al., 2005).

4.2 Methodological Limitations

To evaluate microbial contamination risk, the distance of modelled pit-latrines to vulnerable water-points was estimated from pit-latrine density (Eq. 2). This assumes that water-points are centrally located within a cell known to contain a water-point; water-points could actually be located anywhere within the 3 arc-second cell. Only the density of latrines within the cell containing a water-point is considered for determining the risk of contamination, the dispersion of latrines within the cell is assumed to be random. This may result in the underestimation of the contamination risk in cases where the water-point is localised at the edge of a grid-cell and is at risk from pit-latrine contamination from neighbouring cells with. There may be overestimation in cases where the water-point is localised far away from the pit-latrines within the cell. This was mitigated by aggregating data from 3 arc-second to 30 arc-second resolution, identifying regions with high microbial contamination risk. The model also assumes radial groundwater flow i.e., preferential flow in the predominantly the weathered and fractured rock is not accounted for due to insufficient data on groundwater flow patterns within Malawi (Kalin et al., 2022). Assuming a radial approximation of risk of pit-latrine contamination of water-points is furthermore well established within literature (Chidavaenzi et al., 2000, Francey, 1992, Banerjee, 2011).

Only cells with a functional and in-use borehole, tube-well or dug-wells (vulnerable water-points) were used to estimate the contamination risk. From 2020 to 2070, these water-points may be abandoned, and new water-points constructed. It is also likely there will be more water-point containing cells in 2070 than assumed in the model due to increased water-point construction to meet the needs of the growing population(NPC, 2021). This study may underestimate the number of vulnerable boreholes if there is a significant growth in borehole numbers. It is expected that additional water-points will be constructed in areas with existing boreholes, due to the projected increase in population density and urbanisation, and thus will likely have the same risk of contamination as other boreholes within the modelled area. This is therefore considered to be an appropriate limitation as the study identified regions of high contamination risk. There was no differentiation of the risk between shallow and deep wells, water contamination risks may be higher where shallow wells are used, however as these were a minority of water-points (16.3%), the associated risks were not considered significant for a national level evaluation. Transition from vulnerable water-points to taps and piped water-supplies is also not accounted for (Rivett et al., 2019) as there is no information currently available on which to model these changes. Finally, water-point presence/ absence is a binary measure. If more than 1 vulnerable water-point is present within a cell, it may underestimate the contamination risk. These are assumed to be fitting limitations as the purpose of the study is the identification and prioritisation of areas for policy and management intervention which will still be identified in these cases.

There is uncertainty for population projections, particularly at high resolution over extended periods. Whilst high resolution population projections were utilised to identify vulnerable water-points (3-arc second resolution), results were aggregated to 30-arc second resolution to account for spatial variability and uncertainty in population estimates. The percentage of water-points within a 30-arc second resolution cell (approximately 1km at the equator), was used to identify areas at high risk of contamination providing estimations high risk at 30-arc second resolution, in accordance with high resolution literature population projections within this time frame (Chen et al., 2020; Boke-Olen et al., 2017). To further account for uncertainty in population projections, multiple scenarios of population growth were evaluated under the 5 SSP pathways (KC and Lutz, 2017.; Riahi et al., 2017) .

Latrines are assumed to be co-localised with the population, an assumption employed in the literature (Diaw et al., 2020). Some recommend that latrines should be no more than 50m from houses (Banks et al., 2007), therefore they were assumed to be within the same 90m grid cell as the modelled population. The model accounts for the number of users sharing a latrine by calculating the number of latrine users in the rural and urban areas of the Chikwawa case study from the CJFWFP survey (Kalin et al., 2019). In areas with very high population density, there may be more latrine users per latrine and therefore a lower latrine density than modelled. However, as it is recommended that no more than 20 latrine users share a latrine (Banks et al., 2007), these should still be identified as areas for intervention. Equally, the study may underestimate pit-latrines in very sparsely populated areas as fewer users may share a latrine in this context. Given the focus of this paper is on areas of high latrine density, this is not considered a significant limitation.

The cumulative quantity of faecal waste was used to estimate the mass of residual contaminants in the ground after pit-latrine abandonment (nitrogen, phosphorous, potassium and carbon). The model does not estimate the concentrations of contaminants in groundwater. While the model divides the cumulative loading of waste by the area of WRUs to give an indication of faecal waste density, data is not currently available on the pathways for contaminant mobility or the total volume of groundwater in each WRUs, therefore it was not possible to estimate the concentration within groundwater. Despite these limitations, the indication of areas with a high risk of chemical contaminants should guide further research and monitoring. We propose that there should be increased focus on national sampling efforts to assess chemical contamination of groundwater, accounting for contamination risks from pit-latrines.

Microbial and chemical contamination risks of water-points from pit-latrines assume that there are no barriers to groundwater contamination from faecal waste. Pit-latrines are assumed to be not being emptied, based on estimates that approximately 1% of pit-latrines are undergoing emptying in Malawi (Hinton et al., 2024). Similarly, pit-latrines were assumed to be unlined, around 10-15% of pit-latrines are estimated to be lined nationally (Chiposa et al., 2017, Hinton et al., 2024), where lining is used, interwoven logs and bamboo sticks are commonplace and can provide limited capacity to minimise contamination (Namwebe et al., n.d; Saxena and Den, 2022). Assumptions regarding lining and emptying of pit-latrines are therefore deemed to be justified.

4.3 Future directions

Further work incorporating aquifer volume, recharge, water-table depth, soil hydraulic conductivity and nitrate degradation, would enable better estimation of when groundwater resources may reach tipping points of nitrate levels (Templeton et al., 2015). Cumulative faecal waste and chemical loading estimates assume a constant value for faecal waste and chemical content using estimates for human faeces (Del Porto & Steinfeld, 1999; G.T.Z. Ecosan, 2000;

Strande et al., 2018). Further research could also incorporate spatial variation in faecal characteristics (Gwenzi et al., 2023; Kalulu et al., 2021). Microbial contamination prediction would be enhanced by further work on the variation in the groundwater table, pit latrine depth, soil type, biochemistry (Graham and Polizzotto, 2013; Islam et al., n.d.), hydraulics (Dzwairo et al., 2006), the direction of groundwater flow (Dzwairo et al., 2006; Back et al., 2018) as well as the type, age, and level of damage of the water-point (Escamilla et al., 2013). Temporal dynaMICS could also be considered; accounting for difference in contamination in the dry season and wet season (Mkandawire, n.d.; Pritchard et al., n.d., n.d.). Furthermore, an increased frequency of extreme weather events due to climate change could increase the frequency and severity of water-point contamination from pit-latrines (Rivett et al., 2022). We propose this methodology could be applied to other areas with a high risk of contamination from pit-latrines, particularly in Sub-Saharan Africa (Graham and Polizzotto, 2013; Nakagiri et al., 2016).

We suggest that ongoing work is needed to maintain databases that underpin risk management of pit-latrines to groundwater under rapid population change. This work should also be used to target monitoring of groundwater quality in areas identified as at high risk of contamination. Finally, revisions to the sanitation policy must take groundwater contamination into account to limit effects that could undermine efforts to improve public health.

5 Conclusions

- Using a novel high resolution spatial model of pit-latrine usage, we project microbial and chemical pit-latrine contamination.
- Under all modelled scenarios of population change and sanitation policy, we project and increase in both microbial and chemical pit-latrine groundwater contamination.
- We predict a three-fold increase in the number of water-points at risk of microbial pit-latrine contamination from 2020-2070 under business-as-usual population growth and sanitation policy scenarios.

- Current annual national nitrogen loading in pit-latrines is comparable to nitrogen fertiliser application.
- Dynamic monitoring of sanitary infrastructure risks is needed to manage the growing risk of pit-latrine contamination on groundwater.

Author contributions

R.H, R.K, C.M and M.T designed the study. R.K was PI and managed the CJFWFP data collection. R.H. conducted the formal analysis. R.G.K.H wrote the original draft of the manuscript. R.K, C.M, M.T, M.K and P.M contributed to the writing and reviewing of the final version of the manuscript. R.K. supervised the study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data presented here as well as data for alternative population scenarios and sanitation policy scenarios is available to download on Github (https://github.com/Rebekah-Hinton/Predictive-pit-latrine-groundwater-model). Georeferenced CJFWFP sanitation and water-point data is available online on the mWater portal. Water Resource Units (WRU) and District boundaries were obtained from MASDAP (www.masdap.mw).

Ethics

Informed consent was obtained from all subjects involved in the study. All data collected were in line with the Government of Malawi ethics and was agreed with each participant.

Code availability

Code for the model is available on Github (https://github.com/Rebekah-Hinton/Predictive-pit-latrine-groundwater-model).

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6 Supplementary materials

6.1 Population projections

Supplementary materials Table 1: Supplementary materials Table 1: Comparison of model performance, applying urban smoothing factors, with Worldpop 2020.

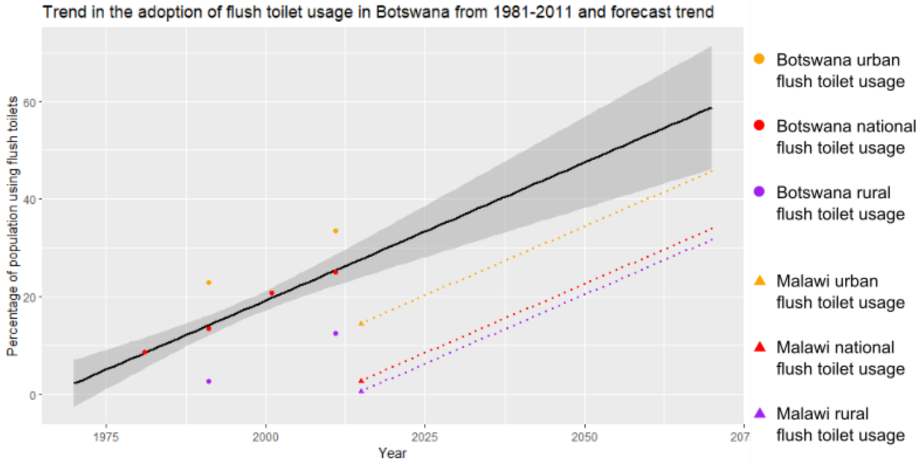
Comparison of modelled population projections, with varying urban smoothing factors applied, for 2020 compared to WorldPop 2020 population projections using root mean square error (RMSE) and the percentage of cells exceeding thresholds of difference at 3 arc-second (Worldpop 100m dataset) and 30 arc-second (Worldpop 1km dataset). For the RMSE calculations, modelled population is compared to both UN adjusted and non-adjusted WorldPop 2020 population distributions and resolutions. The percentage of cells at 3-arc and 30 arc-second resolutions in which the projected population in 2020 differed from the WorldPop 2020 population (non-adjusted) population distribution by more than 1 person, 10 people or 100 people is summarised. The Urban Fraction Smoothing Factor for which there was the smallest number of cases differed between the projected population and WorldPop is highlighted in bold.

Urban Fraction Smoothing Factor	RMSE				Percentage cells where population difference exceeds					
	Non-adjusted		UN-adjusted		1 person/ cell		10 people/ cell		100 people/ cell	
	3 arc-second	30 arc-second	3 arc-second	30 arc-second	3 arc-second	30 arc-second	3 arc-second	30 arc-second	3 arc-second	30 arc-second
1.0	13.46	10.73	13.30	6.87	**6.02**	3.51	**0.25**	0.19	0.03	0.02
0.8	12.10	10.15	11.95	6.20	6.06	3.49	0.26	0.19	0.03	0.02
0.6	10.60	9.46	10.46	5.43	6.12	3.45	0.27	0.20	0.03	0.02
0.4	8.88	8.61	8.78	4.49	6.23	**3.43**	0.28	0.19	0.02	0.01
0.2	6.73	7.42	6.73	3.21	6.49	3.49	0.31	**0.16**	**0.01**	**0.00**

Supplementary materials Table 2: Population of Malawi as estimated from different available gridded population distributions for 2020. Predicted population compared to the WorldBank 2020 population to estimate the percentage error.

Population dataset	Resolution at equator	Estimated Malawi population 2020/million	Percentage difference to World Bank 2020 population
WorldPop 2020	100m	17.94	-6.22
WorldPop UN-adjusted 2020	100m	19.90	+4.00
WorldPop 2020	1km	18.43	-3.68
WorldPop UN-adjusted 2020	1km	23.00	+20.18
Landscan 2020	1km	28.61	+49.55
Boke-Olen et al., ("High-resolution African population projections from radiative forcing and socio-economic models, 2000 to 2100," n.d.) population projection	1km	20.72	+8.32
Hinton et al., population projection	100m	19.06	-1.64

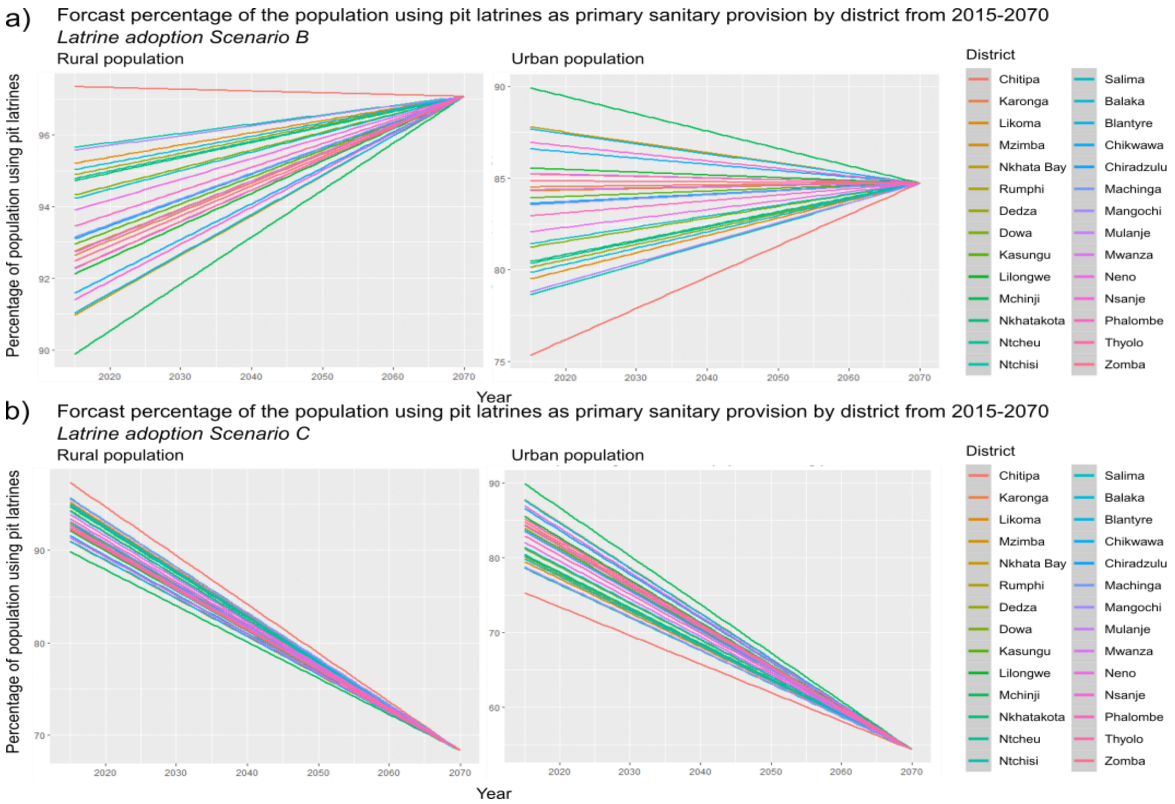
6.2 Latrine adoption scenarios



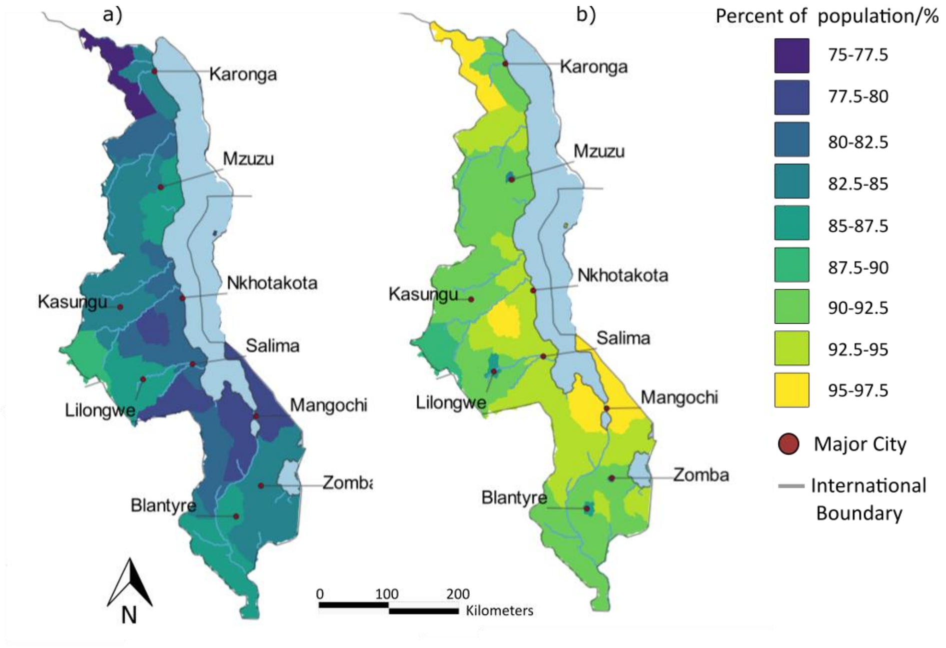
Supplementary materials Figure 1: Forecast percentage of the population using flush toilets for Malawi if Malawi follows the rate of flush toilet adoption seen in Botswana from 1981-2011. The trend in Botswana's flush toilet adoption is shown with data-points as circles. The 2015 DHS survey results for the level of flush latrine adoption in Malawi are represented by the triangles. Orange signifies flush toilet usage in urban areas, red is national and purple is in rural areas. The projected trend for Malawi's flush toilet usage is shown in dashed lines.

Table 3: Summary of 3 urban and rural case-studies in Chikwawa used to estimate the population per pit-latrine. The population was estimated from the 2017 WorldPop population distribution for Chikwawa and summed within each of the areas. The number of pit-latrines within each area was summed from the CJFWFP pit-latrine survey (largely in 2017) in which Chikwawa was most comprehensively mapped.

	Urban area 1	Urban area 2	Urban area 3	Rural area 1	Rural area 2	Rural area 3
Population	6,787	1,200	2,998	51,207	107,404	87,706
Pit-Latrines	934	73	168	3,320	10,084	6,178

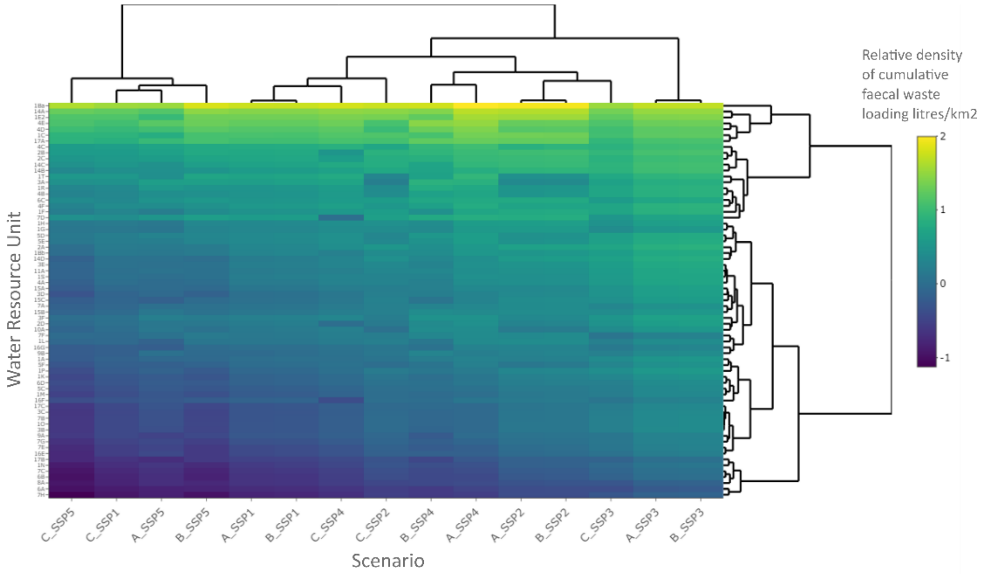


Supplementary materials Figure 2: Summary of pit-latrine using population in sanitation scenarios B and C. a) Forecast percentage of the population using pit-latrines as their primary source of sanitation for rural and urban contexts for different districts in Malawi under latrine adoption Scenario B (increasing pit-latrine usage). Districts have a level of pit-latrine usage in 2015 from the DHS 2015/16 survey. All districts are assumed to have the national average projected level of pit-latrine usage in 2070. b) Forecast percentage of the population using pit-latrines as primary source of sanitation for rural and urban contexts for different districts in Malawi under latrine adoption scenario C (decreasing pit-latrine usage). Districts have a level of pit-latrine usage in 2015 from the DHS 2015/16 survey. All districts are assumed to have the national average projected level of pit-latrine usage in 2070. The level of pit-latrine usage in 2070 is projected by modelling the adoption of flush toilets based on the observed trend in flush toilet usage in Botswana from 1981-2011.



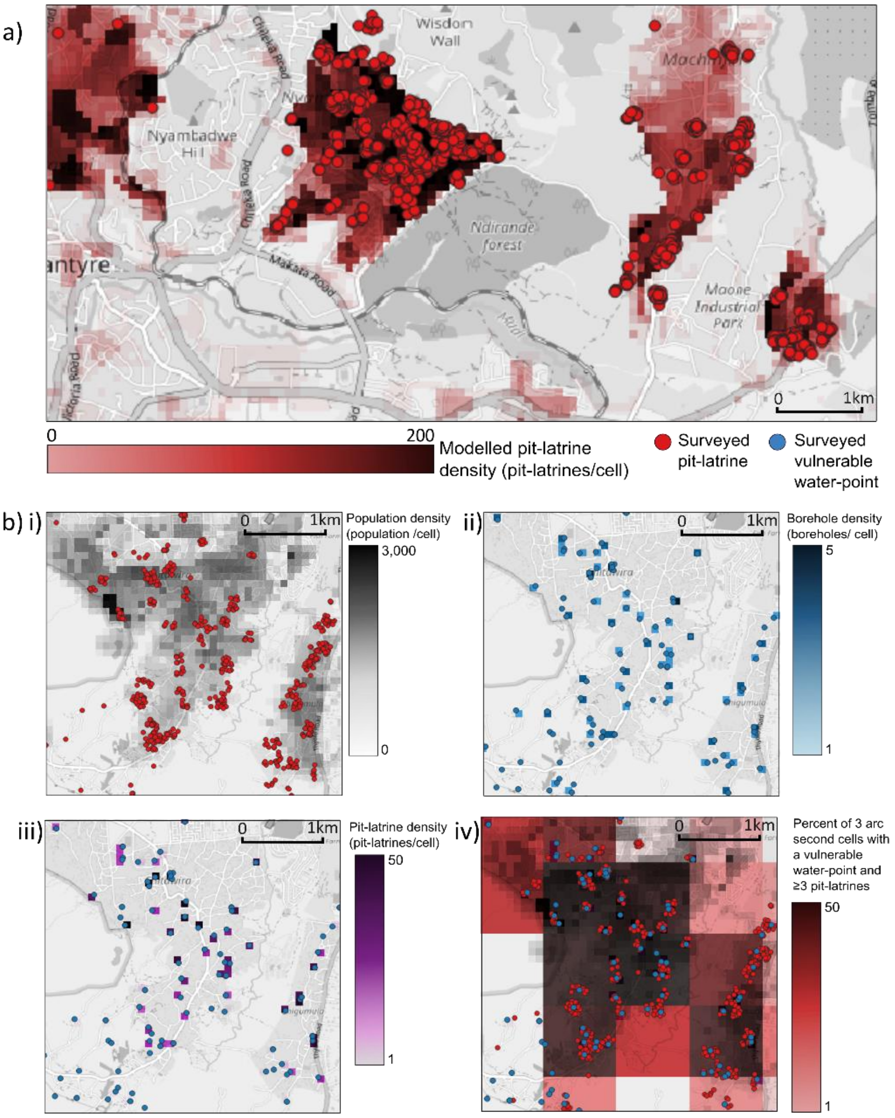
Supplementary materials Figure 3: Spatial variation of pit-latrine usage. Percentage of the 2015 population using pit-latrines as their primary form of sanitation in (a) urban contexts and (b) rural contexts, data from DHS 2015-16 survey.

6.3 Faecal loading



Supplementary materials Figure 4: Double dendrogram showing results of unsupervised hierarchical clustering analysis of faecal loading under multiple sanitation policy and socioeconomic scenarios. Water Resource Unit (WRU) clustering units are organised by row and pit-latrine/ socioeconomic scenarios are clustered by column (Sanitation policy scenario A, B and C and SSP scenarios 1-5). The scale bar is a logarithmic scale of the relative density of cumulative faecal waste loading for the year 2070 with the WRUs with the highest density of faecal waste loading with the highest value. Similarity between WRUs (shown in y-axis) and scenarios (x-axis) is represented by the height of the nodes in the plot with more similar scenarios having shorter nodes. Pit-latrine scenarios A and B show high similarity for all SSP scenarios; however, sanitation policy scenario C typically shows higher similarity to sanitation policy scenarios A and B of lower population growth and urbanisation SSP scenarios.

6.4 Latrine Density



Supplementary materials Figure 5: Example of methodology and results compared with CJFWFP survey data, 2017, for Blantyre. Images made with QGIS using Open Street Map background. a) Example region of North-East Blantyre. Estimation of pit-latrine density for Malawi, 2017 (darker areas have a higher estimated number of pit-latrines). The locations of mapped pit-latrines based on the 2012-2020 CJFWFP sanitation survey are shown as red points (majority of surveys in this region were conducted in 2017).

b) Example of steps in the methodology, applying an example of an area of Southern Blantyre. i) Population density is shown in grey with higher population densities as a darker colour. The locations of mapped pit-latrines are shown as red points. ii) The density of water-points is shown in blue with darker blue with higher densities of water-points within 3 arc-second grid cells. Locations of known waterpoints as blue points. iii) The density of pit-latrines projected as being within the same 3 arc-second grid cell as water-points in shown in purple. Locations of known water-points as blue points. iv) Aggregated data to 30 arc-second grid resolution, the percentage of water-points in a 30 arc-second resolution grid in which there are 3 latrines or more within the same 3 arc-second grid cell as the water-point. Locations of known water-points as blue points and locations of mapped pit-latrines are shown in red.

Supplementary materials Table 4: Number of cases with given densities of pit-latrines per 3 arc-second grid cell across the whole of Malawi for 2020-2070. For the years 2020-2070. SSP 2, Sanitation policy scenario A.

Number of latrines in 3 arc-second grid	2020	2030	2040	2050	2060	2070	Percentage change
No latrines	1,081,167	1,061,816	1,042,209	1,025,595	1,015,103	1,008,596	-6.7%
1-2 latrines	185,588	375748	564,178	724,138	827,361	908,633	+390%
3-9 latrines	37,418	36,647	33,094	28,034	19,046	11,765	-68.6%
10-29 latrines	10,557	13,013	20,421	27,002	33,362	15,242	+44.4%
30-49 latrines	1,671	2,333	4,332	6,401	7,511	9,125	+446%
50-99 latrines	613	1,388	2,681	4,171	6,131	9,445	+1,441%
100+ latrines	162	393	888	1,986	3,237	7,511	+4,536%

Supplementary materials Table 5: Risk to vulnerable water-points. Number of cases of pit-latrines within the same 3 arc-second grid cell in cells as a vulnerable water-point (domestically used borehole, tube well or dug-well) at given thresholds of pit-latrine density for the whole of Malawi. For the years 2020-2070. SSP 2, Sanitation policy scenario A.

Number of latrines in 3 arc-second grid	2020	2030	2040	2050	2060	2070	Percentage change from 2020 to 2070
No latrines	37,889	35,092	32,574	30,670	29,523	28,394	-25.1%
1-2 latrines	3,590	6,297	8,667	10,449	11,557	12,332	+244%
3-9 latrines	1,002	962	803	647	408	1,312	+30.9%
10-29 latrines	242	340	562	723	891	253	+4.6%
30-49 latrines	39	47	97	160	193	170	+336%
50-99 latrines	20	32	54	85	136	181	+805%
Over 100 latrines	11	23	36	59	85	151	+1,273%

5.2.1 Postface

This piece directly answered RQ2 ‘What are challenges to groundwater quality in Malawi?’ through exploring the growing challenge of pit-latrine contamination of groundwater. By developing a novel method to predict pit-latrine density from population-based distribution, the chapter achieved SO4 by predicting current risks of groundwater drinking water supplies from pit-latrines. The work achieved SO5 by evaluating the risk of groundwater contamination from sanitation infrastructure under future scenarios of population growth and sanitation policy. Under current projections of population growth and sanitation policy, Malawi is facing a growing crisis of groundwater contamination from pit-latrines.

Due to its forward-facing perspective, this study refrains from assessing measured groundwater contamination therefore limiting evaluation to the risk of contamination rather than measured levels of contamination. This is addressed within the subsequent piece of work which investigates the origins of groundwater contamination and analyses the importance of sanitation infrastructure in relation to national-level microbial and nitrate groundwater pollution (SO6).

5.3 Mixed method analysis of anthropogenic groundwater contamination of drinking water sources in Malawi

Rebekah G.K. Hinton[1,2], Robert M. Kalin[1], Limbikani Banda[1,3], Modesta B. Kanjaye[4], Christopher J.A. Macleod[2], Mads Troldborg[2], Peaches Phiri[3], Sydney Kamtukule[3]

[1] Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow G1 1XJ, UK
[2] The James Hutton Institute, Craigiebuckler, Aberdeen AB15 8QH, UK
[3] Department of Water Resources, Ministry of Water and Sanitation, Government of Malawi, Private Bag 390, Lilongwe, Malawi
[4] Department of Sanitation and Hygiene, Ministry of Water and Sanitation, Government of Malawi, Private Bag 390, Lilongwe, Malawi

Corresponding author: Rebekah Hinton. Rebekah.hinton@strath.ac.uk

Abstract

Groundwater contamination poses significant challenges to public health and sustainable development in Malawi, where approximately 80% of the population relies on groundwater sources for drinking water. This study investigates the presence and drivers of nitrate and *E.coli* contamination in groundwater used for drinking. Analysis was conducted on results from 2,993 boreholes/tube wells for nitrate contamination and 2,418 groundwater drinking water sources for *E.coli* contamination. Overall, 6.11% and 57.2% of water-points did not meet WHO guidelines for safe drinking water quality for nitrate and *E.coli* contamination respectively. Through a mixed-method approach, utilizing generalised linear mixed models and random forest modelling, the study identifies sanitation-related factors as critical drivers of both nitrate and *E coli* contamination. Pit-latrine usage specifically was identified as a particularly important sanitation factor with pit-latrine density resulting in better model prediction than population density for nitrate and *E.coli.* The potential to apply stable isotope methods to validate predictions and monitor nitrate in drinking water was piloted. Overall, this study underscores the urgency of addressing sanitation-related contamination to ensure access to clean drinking water in low-income settings.

Key words: Groundwater contamination, *E.coli,* nitrate, isotope analysis, generalised linear model, random forest

1. Introduction

Groundwater is a critical resource, supplying safe and accessible drinking water for over 2 billion people globally (Kundzewicz and Döll, 2009). Globally, 1.23 million deaths per annum are attributed to unsafe water, with the burden of unsafe water twice as high in low-income countries (IHME, 2019). As a result, groundwater contamination poses an important concern for human health (Karunanidhi et al., 2021). Alongside human health repercussions, safeguarding groundwater quality is essential for environmental and ecosystem preservation (Li et al., 2021).

Contaminants are commonly categorised as deriving from natural or anthropogenic sources (Li et al., 2021). Natural geogenic contaminants originating from minerals in the earth's crust, such as arsenic and fluoride, are common groundwater contaminants and at high levels can pose a concern to human and environmental health (Rivett et al., 2019, Addison et al., 2020, 2021; Kushawaha and Aithani, 2021; Li et al., 2021). Anthropogenic sources of contamination include agriculture or domestic wastewater (Li et al., 2021). Contaminants of anthropogenic origin pose a particular concern as they are increasing as a result of population growth, urbanisation, industrialisation, and agricultural intensification (Li et al., 2021) making the understanding of anthropogenic groundwater contamination a pressing issue.

Nitrogen is one contaminant of concern that is related to human activity. Whilst nitrate may naturally occur in the environment as part of the nitrogen cycle, anthropogenic sources, predominantly from agriculture and domestic wastewater, are major causes of nitrogenous compounds in groundwater (Justin et al*.,* 2021; Harper et al., 2017.) High nitrate levels have been associated with increased infant methemoglobinemia 'blue baby' syndrome as well as linked to some cancers (Puckett et al., 2011.; Rahman et al., 2021.).

Emphasis is often placed on agricultural sources for nitrate contamination, with high nitrogen fertiliser application rates resulting in diffuse nitrate contamination of groundwater resources (Harper et al., 2017; Wick et al., 2012). However, this is not always the case. An analysis of the sources of nitrate contamination in Africa found that population density was a better indicator of groundwater nitrate contamination than fertilizer application on a continental level, with a lack of sanitation hypothesised to be the cause of the elevated contamination in areas of high population density (Ouedraogo et al., 2019). Consideration of human wastes must therefore be embedded in the rhetoric surrounding nitrate groundwater contamination.

Alongside nitrate contamination, inadequate sanitation and domestic wastewater management has also been identified as a critical driver of microbial groundwater contamination (Back et al., 2018). A lack of sanitation infrastructure, resulting in open defecation has been linked to contamination of groundwater used for drinking water in Asia and Africa (Kayembe et al., 2018; Okullo et al., 2017). However, poor domestic wastewater management and sanitation infrastructure can also cause groundwater contamination where wastewater is inappropriately discharged or leaked (Sridhar and Parimalarenganayaki, 2024) or where there is direct contamination from the sanitation infrastructure itself. Pit-latrines provide one example of how sanitation can result in direct microbial groundwater contamination. Serving as the primary source of sanitation for 1.8 billion people globally, pit-latrines are an integral component of sanitation internationally (Gwenzi et al., 2023). However, unless safely managed, pit-latrines can result in groundwater contamination (Banks et al., 2007.; Chidavaenzi et al., 2000.; Dzwairo et al., 2006.; Escamilla et al., 2013.; Graham and Polizzotto, 2013.; Gwenzi et al., 2023; Islam et al., 2016; Ndoziya et al., 2019.; Tillett, 2013.; Wright et al., 2013), a particular concern when they are used in contexts with a high reliance on groundwater sources of drinking water (Graham & Polizzotto et al., 2013).

Anthropogenic groundwater contamination sources intersect with environmental considerations; this is particularly seen in the case of climate-change related rainfall intensity. Heavy rainfall can result in groundwater contamination of nitrate through leaching of nitrate from fertilizer, particularly during extreme precipitation (Bijay-Singh & Craswell, 2021). Similarly, microbial contamination from both open defecation and pit-latrines is heightened under extreme rainfall, resulting in contaminated surface runoff infiltrating boreholes (Aralu et al., 2022), the risk of which is increased in poorly maintained boreholes (Rivett et al., 2022). In addition, the increased water table height following heavy rain can result in greater pit-latrine effluent leaching into groundwater and contamination of boreholes (Rivett et al., 2022). Not only does this highlight the significance of environmental context on anthropogenic contamination, but the increasing risk of contamination also following extreme rainfall presents a growing challenge of managing groundwater contamination from sanitation under climate change.

Malawi represents a particularly pertinent case study in the consideration of groundwater quality management with one of the lowest levels of access to safe drinking water globally (UNICEF & WHO, 2024). Groundwater provides the main source of drinking water for almost 80% of the population, (NSO, 2021) making groundwater quality essential to providing safe drinking water provision. Currently, over 60% of the population access drinking water from contaminated drinking water sources (NSO, 2021). Poor quality water infrastructure worsens the contamination crisis; polluted surface run-off water can contaminate damaged or poor-quality boreholes through cracks in the concrete apron (Rivett et al., 2022). This is particularly a concern in Malawi due to high rates of borehole non-functionality and minimal borehole maintenance (Truslove et al., 2019; 2020; Kalin et al., 2019) placing water infrastructure itself at a greater risk of contamination.

The challenge of groundwater contamination at drinking water sources is exacerbated by a low level of water treatment, with over 60% of the population not conducting water treatment (NSO, 2021). Even where water treatment is conducted, it is largely through inefficient treatment processes such as bleach chlorination (Nielsen et al., 2022). This makes any contamination of groundwater at water sources likely to result in direct consumption of contaminated drinking water. As such, inadequate groundwater quality is undermining Malawi's aim to provide 100% of the population with clean water sources by 2030 (NPC, 2021).

The consequences of high levels of contamination of drinking water sources can be seen in the burden of waterborne disease within Malawi, estimated to account for over half of the national disease burden (Chavula, 2021). Malawi's deadliest cholera outbreak occurred from 2022 to 2023 and was reported to be partially due to widespread drinking water contamination (Sokemawu Freeman et al., 2024). There have been growing concerns of faecal groundwater contamination from pit-latrines as a factor in the high burden of waterborne disease with cases of microbial pit-latrine contamination already reported (Pritchard et al., 2007; 2008). This is likely to worsen as under current population growth scenarios there is projected to be a three-fold increase in the number of water-points at high risk of pit-latrine contamination due to proximity (Hinton et al., *in review*).

Managing sources of groundwater contamination is a public and environmental health priority, particularly in Malawi. Effective management of groundwater quality requires enhanced understanding of areas at high risk and sources of contamination. Yet, the multiple pathways for borehole and groundwater contamination (Rivett et al., 2022), as well as multiple sources of contaminants, make analysis of the sources of contamination of groundwater challenging. Furthermore, contaminants such as nitrate can be retained in groundwater for extended periods therefore travelling large distances and making tracing of sources especially difficult (Canter, 1996).

Isotope hydrology is a commonly used method to evaluate groundwater resources and has been widely used for tracing sources of nitrate contamination around the world, (Kendall et al., 2007; Minet et al. 2017, Jung et al., 2020, Nikolenko et al., 2018). By analysing the relative abundance of nitrogen and oxygen isotopes, likely sources can be identified due to characteristic patterns of isotope abundance, developing 'signatures' of the source of contamination. Whilst this method is highly effective, the need for specialised analytical facilities, not normally available in lower income countries, makes application of the method challenging. In addition, this method requires multiple geochemical signatures to identify whether sources are from animal manure or human faecal waste due to their similar isotopic signatures (Kendall et al., 2007).

Statistical models including generalised linear modelling and random forest regression can provide insight to the relationships between predictor variables and measured groundwater contamination. These models can be applied to enhance understanding of the sources of groundwater contamination (Ouedraogo et al., 2019) as well as predict areas likely to have high levels of contamination (Charulatha et al., 2017; He et al., 2022). Both aspects, inform understanding of sources and predicting contamination, are integral to informing policy and managing anthropogenic groundwater contamination. Generalised Linear Mixed Models (GLMM) and Random Forest (RF) provide two such statistical models that can be used to enhance understanding of groundwater contamination (Jena et al., 2023; Ouedraogo et al., 2019; Tyralis et al., 2019, Charulatha et al., 2017). Both models are particularly useful in their application to a broad range of data types and capacity to handle non-linear relationships (Liu, 2016; Louppe, 2014). GLMM models, alongside other linear regression models, have been used widely to explore sources of contamination of groundwater (Charulatha et al., 2017; Nolan and Hitt, 2006). They have benefit in robustly exploring the relationship between a response variable and predictor variables particularly as GLMMs can account for random effects as well as fixed effects (Rabe-Hesketh and Skrondal, 2008; Muschelli et al., 2014). As such they have been widely used to explain patterns in data in multiple fields (Goldstein and de Valpine, 2022; Zhu et al., 2007). However, as with all linear regression models, GLMM models are held back by their limited capacity to handle collinearity of variables (Hendrickx & Nutricia, 2018). This is a common challenge when investigating anthropogenic sources where multiple variables, e.g. population density and sanitation usage, are highly correlated, reducing model efficiency and making them less useful for accurate prediction.

RF models can also be used to analyse and predict contamination trends. They have high predictive performance power (Couronné et al., 2018) particularly for spatial data (Hengl et al., 2018). The RF model functions is a combination of multiple decision trees with each tree applying a different subset of predictor variables to predict the response variable of the training dataset (Rokach and Maimon, 2015; Nath et al., 2022). They are particularly useful for collinear variables (Louppe, 2014). RFs indicate which predictor variables are most important in a specific model prediction (Ishwaran, 2007). However, variable importance must be interpreted with caution and cannot necessarily be used to indicate which are the most important predictor variables for the phenomena being studied (Louppe, 2014). As such, RFs have limited capacity in analysis of sources of contamination but are valuable for efficient prediction. In recognition of their specific strengths and limitations, combinations of GLMM and RF models have been utilised to enhance analysis and prediction (Bernaisch, 2022) and have been applied to studies of groundwater contamination (Ouedraogo et al., 2019; Charulatha et al., 2017; He et al., 2022; Nolan and Hitt, 2006).

This study adopts a multimethod analysis, using both GLMM and RF models to explore groundwater contamination from multiple anthropogenic sources; both exploring sources of contamination (using GLMM) and predicting areas at high risk of contamination (using RF). Both methods are applied to two examples of contamination that are of concern in Malawi, microbial contamination (*E.coli* groundwater contamination) and nutrient contamination (nitrate contamination). Specifically, this work addresses the following research questions: (1) What are the primary sources of nitrate and microbial groundwater contamination in Malawi? (2) What areas are predicted to have highest nitrate and microbial contamination? (3) Evaluate the potential of stable isotopes of nitrate as a tool for nitrate source evaluation and verification of the model results in Malawi. These inferences provide valuable insight into groundwater management, informing decision making on contamination sources as well as identifying areas of concern for contamination and guiding areas for future water quality testing.

2. Methodology

2.1 Context and study area

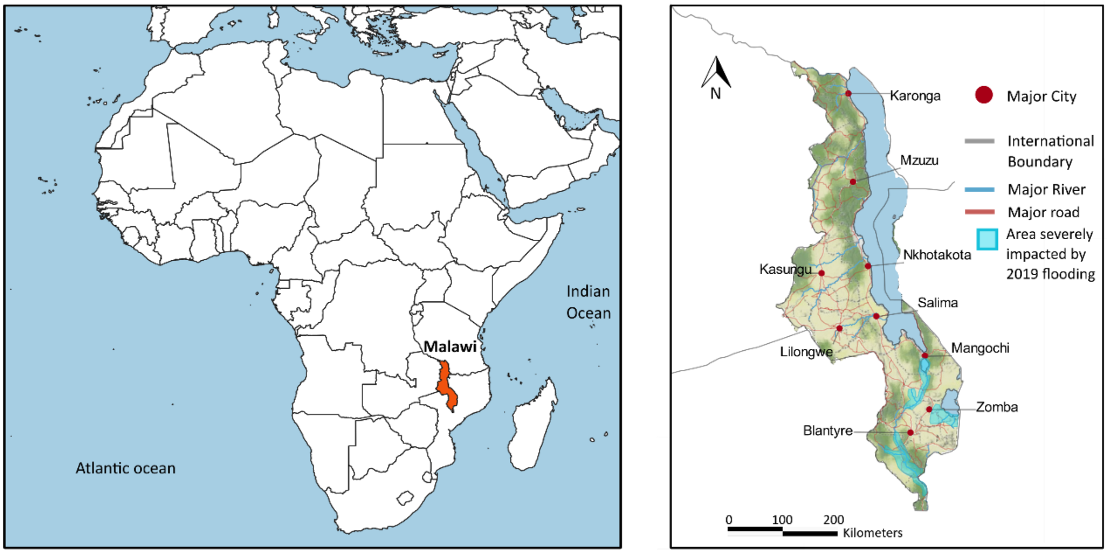


Figure 7: Study location of Malawi showing major cities and rivers. Water quality data from across the country is analysed. Figure was produced in QGIS with Stamen Terrain background (QGIS, 2024).

Malawi is a country in South-Eastern Africa. It experiences a tropical-continental climate with a wet season from November to April and a dry season from May to October (Kalin et al., 2022). Malawi's water supplies are dominated by Lake Malawi, both in framing and quantity. Despite being often overlooked, groundwater is a central resource not only because 82% of water abstraction for agricultural, domestic, and industrial purposes comes from groundwater in rural areas (Fraser et al., 2020), but also as it provides significant provisions to maintain river flows (Kelly et al., 2020). This is particularly true for the dry season where over 90% of all river flow comes from groundwater discharge (Kelly et al 2020**)**. Increasing agricultural intensification is impacting Malawi's land and water management. Currently, the majority (over 80%) of the population are employed in small-holder, subsistence farming (NPC, 2021), planned economic and agricultural development involves increased irrigation and fertilizer usage to increase crop yields (MAIWD, 2018).

Malawi is undergoing rapid demographic change with its current population of 21 million (World bank, 2024) anticipated to reach almost 60 million by the end of the century (United Nations, 2024). Urbanization is resulting in dramatic demographic shifts with the current 84% of the population currently residing in rural areas anticipated to reduce to 40% by 2063 (NPC, 2021. Groundwater forms the main source of drinking water for 80% of the population (Kalin et al., 2022, NSO, 2021) with water from boreholes/tubewells providing the main source of drinking water and used by 64% of the population (NSO, 2021). Access to safely managed drinking water, defined as an 'improved water source that is accessible on premises, available when needed and free from contamination (WHO and UNICEF, 2017) is low with only 18% of the population meeting guidelines for a safely managed drinking water source (UNICEF and WHO, 2024), despite 88% of the population having access to an improved drinking water source (NSO, 2021). Contamination is a major barrier to access of safely managed drinking water access with over 60% of the population's source of drinking water having measurable *E.coli* contamination (NSO, 2021).

2.2 Water quality data collection for nitrate analysis

Groundwater quality samples were collected from 3,717 boreholes across Malawi. Samples were collected by Government of Malawi water laboratory staff through borehole construction contractors after drilling of a new borehole. Data from individual water quality samples was gathered across Malawi. Samples were collected between 2000 and 2022, with most data collection from 2015 onwards due to increased drilling efforts related to rapid population growth. Data was provided by the Government of Malawi, Ministry of Water and Sanitation for this study. Of the analysed samples, 2,993 were chosen for modelling after removing duplicate responses. The threshold of 50 mg NO_3^-/L is considered high nitrate according to the Malawi Standard (MS733:2005) for drinking water from boreholes and protected shallow wells and the WHO guideline standards (MBS, 2017; WHO, 2017).

2.2.2 Nitrate analysis method

Water samples for nitrate analysis were collected in polyethylene bottles that were rinsed with distilled water, un-acidified, and stored at 4 °C during transportation to the government water laboratory in Malawi. The water samples were filtered through 0.45 µm Whatman filters prior NO_3-N analysis and measured against known laboratory standards. Before 2019, the HACH Chromotropic acid method was used with a HACH spectrophotometer. After 2019 samples were analysed using Ion Chromatography (Ion Analyzer—Model: IA-300). The NO_3-N analysis was performed following the International Standard Methods (APHA et al., 2005), and the accuracy of the results was confirmed through a series of quality assurance and quality control procedures specified in the International Standard Methods (APHA et al., 2005).

2.2.3 Water quality data collection for E.coli analysis

Water quality *E.coli* levels were obtained from the Multiple Indicator Cluster Surveys (MICS); a nationally representative survey between December 2019 - August 2020 of 26,882 households in 1,111 clusters. This survey was conducted by the Government of Malawi National Statistical Office in collaboration with UNICEF (UNICEF, 1995). The survey sample was based on the 2018 Population and housing Census designed to provide representative clusters across the country. Surveys gathered household level information on a range of topics relevant to child, maternal, and family well-being. In addition to household survey responses, the MICS survey conducted water quality testing data at households' sources of drinking water, evaluating *E.coli* levels in household and source drinking water (Bain et al., 2021; NSO, 2021). Water quality testing was conducted at 2,810 water points within the 1,111 clusters nationally. Georeferenced water quality data was provided by the Malawi National Statistical Office, UNICEF Malawi and Global

MICS team. Following data cleaning, 2,801 complete and unique data points were selected. We evaluate data from only groundwater drinking water sources, 2,418.

2.2.4 E.coli analysis method

E.coli water quality analysis followed a protocol outlined in the 2016 MICS Water Quality Testing Manual (UNICEF, 2016). A 100ml water sample was obtained at sources of drinking water, reported to be used by households. Prior to collection from the source, water was flushed for 30 seconds. Water samples were collected in sterilized 'Whirl Pak Bags', the water sample was subsequently filtered through a filter which was placed on an agar growth medium and incubated for 24 to 48 hours and bacterial colony growth counted and recorded (UNICEF, 2016). The number of *E.coli* in a 100ml sample of water was evaluated with values between 0-100 *E.coli* recorded as the number of *E.coli* and values exceeding >100 *E.coli* classed listed as 101 *E.coli/* 100ml.

As values exceeding 100 *E.coli* were not quantified, for the purposes of this study, binary classifications of *E.coli* contamination of water-points were created with water-points classified as any *E.coli* contamination (>0 *E.coli/*100ml) and cases of very high *E.coli* contamination (≥100 *E.coli/*100ml). Whilst *E.coli* contamination indicators were available for both source and household drinking water, we consider only source contamination.

2.3 Water quality data visualisation

For data visualisation, binary contamination data of the presence of nitrate and *E.coli* contamination was rasterized to 10km resolution using the rasterize() function within the raster package, R (Hijmans, 2024). The percentage of surveys conducted within each cell that exceeded given thresholds of contamination were calculated and summarised.

2.4 Statistical model variable selection

A range of socioeconomic and biophysical variables were selected for analysis within statistical models of groundwater contamination. Variables were selected based on the variables analysed in published methods (Ouedraogo et al., 2019, He et al., 2022) or where the literature suggested that greater exploration into specific variables (e.g. sanitation infrastructure) was needed (Ouedraogo et al., 2019).

The selected variables are summarized in Table 1. Summary plots of spatial data used are shown in supplementary information.

Table 5: Variables used in statistical analysis based on literature of nitrate and microbial contamination statistical models

Variable	Description	Source
WRU latrine user density	Water resource scale density of total faecal waste loading into pit-latrines. Total pit-latrine users / area of water resource unit (WRU).	(Hinton et al., *in review*)
Latrine density	Density of pit-latrines in use	(Hinton et al., *in review*)
Open defecation	Density of population practicing open defecation	
Flush toilet	Density of population using flush toilet systems	

Fertiliser	Nitrogen Fertilizer Application	(Potter et al., 2010; Potter, 2012)
Population density	Population density 2022 100m resolution	Worldpop gridded population distribution (Worldpop, 2024)
Manure	Nitrogen manure production	(Potter et al., 2010; Potter, 2012)
Flooding	Binary classification of whether highly impacted by 2019 flooding	
Precipitation	Overall trend in precipitation	(RCMRD, 2015a)
Cropping intensity	Indicator of cropping intensity	(FAO/NASA, 2023)
Anthropogenic Biome	Measure of human impact (cropland, urban areas) vs ‘wildness’	(RCMRD, 2015b)
GDRI poverty	Global Gridded Relative Deprivation Index	(CIESIN, 2022)
Livestock	Total density of sheep, goats, pigs and cattle	Gridded Livestock of the World (GLW 3) database(Gilbert et al., 2018)
Source of water	Drinking water source. Available only for MICS survey data.	MICS survey (NSO, 2021)
Date of sample collection	Date (month and year) of sample. Available only for MICS survey data	MICS survey (NSO, 2021)

Analysis of the distribution of different types of sanitation was identified as an area of interest. The types of sanitary facility provision considered were pit-latrine use, flush toilet use, and open defecation (no facility) as these make up the majority of sanitary access (Hinton et al., 2023). National spatial data regarding the type of sanitation was only available for pit-latrine usage.

For flush latrine usage and open defecation, spatial sanitation use data was produced following methodology outlined in (Hinton et al., *in review*). A high resolution, 100m, gridded population distribution of Malawi obtained from WorldPop population distribution (Worldpop, 2024) was defined as rural or urban areas based on the urban fraction outlined in (Hurtt et al., 2011). The rural and urban population for each district was multiplied by the respective level of sanitary facility use (or open defecation) for rural and urban populations as outlined in the 2015/16 DHS survey (NSO & ICF, 2017).

Another variable of interest was flooding extent. The 2019 Cyclone Idai flood was taken as a flooding event of interest as it was representative of flooding events observed and was close to when most analysed data was collected. Flooding data was generated as a binary raster of areas impacted by flooding in 2018-2019, corresponding to the years leading up to water quality survey sampling. The raster was created in QGIS (QGIS, 2024), creating a map of flooded areas as reported in flooding report survey data (DoDMA, 2019 ; Scottish Government, 2019) and informed by stakeholder engagement (personal communication).

Specific livestock data was available from the gridded Livestock of the World (GLW 3) database (Gilbert et al., 2018) however, for the purposes of this study information for total livestock was of interest**.** Total livestock data was calculated by summing the quantity of sheep, cows, pigs, and goats from the ridded Livestock of the World (GLW 3) database (Gilbert et al., 2018) as these are the major mammalian livestock cultivated in Malawi. Maps of all data is presented in Supplementary Information.

For *E.coli* contamination data, water sample information on the type of water resource and the date of collection (month and year) was also included in model generation. Boreholes/

tubewells were the most commonly used sources of groundwater drinking water, the types of water sources are summarised in the appendix.

2.5 Multiple linear regression model construction

This study employed generalized linear mixed model (GLMM) structures to explore the relationship between response and predictor variables, accommodating noncontinuous as well as continuous variables with both fixed and random effects (Liu, 2016; Rabe-Hesketh and Skrondal, 2008). Three models of contamination were developed using binary response variables, the response variables in the respective models were the presence of high nitrate, any *E.coli* presence, and high *E.coli*. In each model, the response variable was modelled as a binary variable of whether contamination passed given thresholds.

For NO_3, the threshold for 'high nitrate was values of 50mg/L or above of NO_3 according to national and WHO guidelines (MBS, 2017; WHO, 2017.). For *E. coli* contamination, two GLMM models were constructed. The first *E. coli* GLMM model considered the presence of any *E. coli* contamination, therefore exceeding WHO specifications of safe drinking water (UNICEF & WHO, 2024). The second model considered high *E.coli* contamination, exceeding 100 *E.coli* /100ml and considered as a 'very high' risk (NSO, 2021). All GLMM models used logistic regression as they applied continuous and categorical variables to a binary predictor.

All models were produced using the feGLM function in the fixest package (Berge, 2023), R (R Core Team, 2023), as this enabled GLMM generation with and without fixed effects (Bergé, 2018). For NO_3 contamination, a GLMM model with no fixed effects was constructed with continuous and categorical predictor variables and a binary NO_3 response variable. For *E coli* contamination, consistent data was available on the water source type and date of collection and were used as fixed effects. Within the *E.coli* contamination GLMM water source and date (year and month) were included as fixed effects. The number of levels for each fixed effect is summarized in the model structure in the supplementary information. Both *E.coli* contamination models therefore had a binary contaminant response variable with categorical and continuous predictor variables with fixed and random effects.

GLMM probabilistic assumptions of linearity, response distribution, independence and multi-collinearity were confirmed using the R functions lm and the Variance Inflation Factor (VIF) (Chambers, 1992; R Core Team, 2023; Wilkinson and Rogers, 1973). Diagnostic plots and VIF factors are provided in Supplementary Information. There was high multi-collinearity between the latrine density and population predictor variables. To account for this, two GLMMs were generated for each contaminant model, one with population as a predictor variable and one with latrine density as a predictor variable. The model performance of the two GLMMs for each contaminant (with either population or latrine density) was evaluated and the model with best overall performance is summarised within the results. For NO_3, there was a high multi-collinearity between the predictor variables, flush toilet use, and open defecation. To resolve this case, one of the variables with very high multiple collinearity (flush toilet use) was removed, VIF values before and after the removal of flush toilet usage are shown in the appendix. Following the removal of variables with high multi-collinearity, all VIF values were below 3 and therefore met the assumptions of multi-collinearity (James et al., 2013).

Data was subset into training and testing data, using 60% training to 40% testing data. The GLMM model was applied to predict testing data outcomes using the R predict function (R Core Team, 2023), predicted contamination was compared to measured data and a confusion matrix produced. Metrics for model evaluation are summarized in Equations 1-4. Model performance metrics are accuracy (proportion of cases correctly categorised) (Equation 1), precision (proportion of positive cases identified) (Equation 2), sensitivity (proportion of predicted positives that were true positives) (Equation 3), and specificity (proportion of negatives that were true negatives) (Equation 4). Model fit was also evaluated using the McFadden pseudo R^2 (McFadden, 1974) (Equation 5), calculated within the feGLM function, fixest package (Berge, 2023), R. For MacFadden pseudo R^2, values between 0.2 to 0.4 'represent and excellent fit'(McFadden, 1977).

$$\textit{Accuracy} = (TP+TN) / (TP+TN+FP+FN) \quad (1)$$

$$\textit{Precision} = TP / (TP+FP) \quad (2)$$

$$\textit{Sensitivity} = TP / (TP+FN) \quad (3)$$

$$\textit{Specificity} = TN / (TN+FP) \quad (4)$$

$$R^2_{McF} = 1 - \ln(L_M) / \ln(L_0) \quad (5)$$

Where TP is true positive (the number of cases predicted as positive correctly), TN is true negative (the number of cases predicted as negative correctly), FP is false positive (the number of cases predicted as positive incorrectly) and FN is false negative (the number of cases predicted as negative incorrectly). R^2_{McF} is the MacFadden pseudo R^2, L_M is the likelihood of the fitted model and L_0 is the likelihood of the null model.

For the models of NO_3 contamination and high *E.coli* contamination presence, there was imbalance in the dataset with only a small percentage of samples exceeding the given thresholds. To improve model development, the minority class was upsampled using the upsample() function under the caret package in R (Kuhn, 2008) to make class distributions equal.

2.6 Random Forest Model construction

For spatial prediction of areas of contamination, random forest modelling was applied using the package randomForest in R (Breiman, 2001; Liaw and Wiener, 2002)**.** The number of decision trees was set as 500, considered to be an appropriate balance to limit overfitting. All given spatial predictor variables were included in the model for both NO_3 and *E.coli* level. For NO_3 contamination, a continuous response variable for NO_3 was predicted therefore an unsupervised regression random forest model was generated. For *E.coli* contamination, two binary models of *E.coli* contamination were produced: presence of any *E.coli* contamination and *E.coli* contamination of 100 *E.coli*/100ml and above. For the generation of these random forest models, classification unsupervised random forest models were produced.

Data was split into training and testing datasets, using 70% for model training and 30% for testing. Model performance was evaluated by calculating the Root Mean Square Error (RMSE), summarized in Equation 5, and R^2 coefficient for the continuous, regression model, of NO_3, Equation 6.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y})^2} \quad (5)$$

$$R^2 = 1 - \frac{\sum(y_i - \hat{y})^2}{\sum(y_i - \bar{y})^2} \quad (6)$$

Where N is the number of data points, y_i is the given value of y, $\hat{y}$ is the predicted value of y, and $\bar{y}$ is the mean value of y.

For categorical model prediction of *E.coli* contamination, model performance was evaluated using a confusion matrix to calculate model accuracy, precision, sensitivity, and specificity (Equations 1-4). Feature importance was evaluated by calculating Shapley values of variables in the Random Forest Model, comparing model predictions with and without features being included, model simulations were iteratively run to give different feature orders. Shapley values were calculated using a randomly assigned 5% subset of the data due their computationally intensive nature. The kernelshap() function, within the kernelshap package in R (Mayer et al., 2023), was used to calculate Shapley values. Shapley values were visualized as a beeswarm plot using the shapviz() and sv_importance() functions within the shapviz package, R (Mayer and Stando, 2024).

For visualisation of predicted contamination, the random forest models were applied to create a raster of predicted contamination. The NO_3 model generated a predicted NO_3 concentration raster for the average level value of NO_3 contamination for a water-point within a given 10km cell. For the *E.coli* models, the percent for water points within a given 10km cell that would exceed thresholds of *E.coli* was predicted. Predicted rasters were produced by applying the random forest model to a raster stack of all predictor variables using the predict() function under the raster package in R (Hijmans, 2024). Maps of predicted contamination were produced in QGIS for visualisation (QGIS, 2024).

2.7 Isotope analysis

A pilot study using nitrate isotope analysis was undertaken within the Linthipe river sub-catchment (Kalin et al., 2022b) in the central region of Malawi. The dominant aquifer type within the Linthipe sub-catchment is a colluvium overlying weathered and fractured basement (Kalin et al., 2022b) with extensive groundwater-surface water connections within the region. Pilot samples were collected as part of an International Atomic Energy Agency (IAEA) national project (MWL-7002 TC project). Targeted groundwater and surface water samples were collected at 15 locations suspected of high nitrate concentrations between May and June 2015 and shipped to the IAEA (Vienna) for analysis of $\delta^{15}N$ and $\delta^{18}O$ of NO_3^-.

2.7.1 Analytical methods for isotope analysis

Water samples were collected in 60mL HDPE bottles tapped tightly to prevent evaporation and exchange with atmospheric water vapor and stored in cool conditions (4 ^{o}C) during transportation and holding at the Isotope Hydrology Laboratory of the IAEA (Vienna, Austria). The $\delta_{15}N$- NO_3^- and $\delta^{18}O$-NO_3^- were measured using dual isotope approach and results were reported in per mil (‰) relative to atmospheric air (N2) and Vienna Standard Mean Ocean Water (VSMOW) standards for nitrogen and oxygen, respectively (equations 7 and 8). International reference materials (IAEA-NO_3^-, USGS34 and USGS35) were used for data calibration and instrumental monitoring. Analytical precision was less than ±0.2‰ for δ_{15}N-NO_3^-, and ±0.5‰ for δ^{18}O-NO_3^-, respectively.

$$\delta^{15}N(‰) = (((^{15}N/^{14}N)\ sample - (^{15}N/^{14}N)\ standard) -1) \times 1000 \qquad (7)$$

$$\delta^{18}O(‰) = (((^{18}O/^{16}O)\ sample - (^{18}O/^{16}O)\ standard) -1) \times 1000 \qquad (8)$$

3. Results

3.1 High Nitrate and E.coli distribution in groundwater

The percent of surveyed water points within 10km grid cells passing thresholds of contamination of water points passing thresholds of contamination is summarized in Figure 2. A map of surveying intensity is provided in the Supplementary Information, Figure 2.

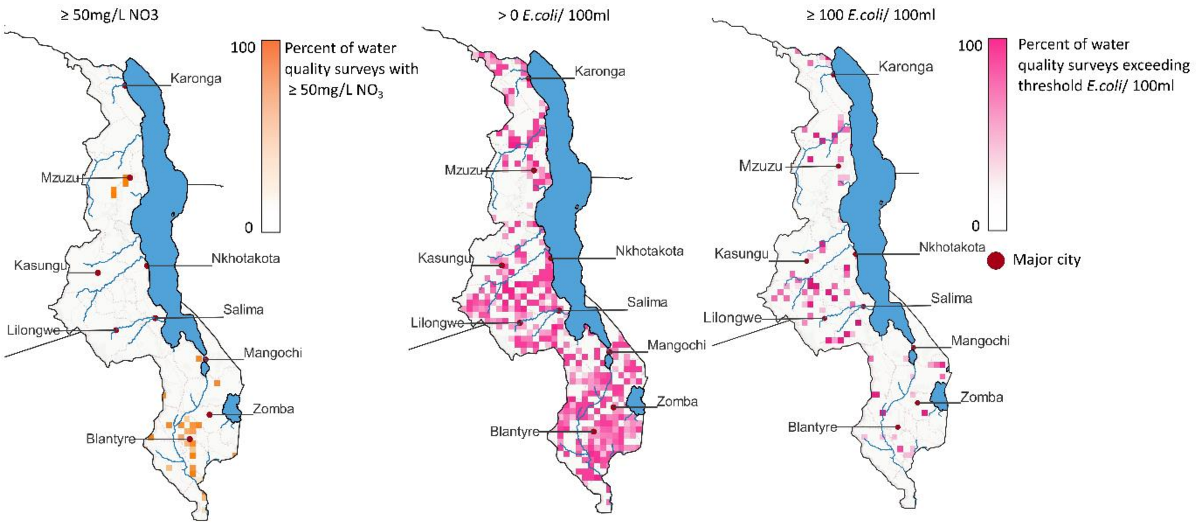


Figure 2: The percent of groundwater samples within a 10km grid exceeding thresholds of drinking water quality for nitrate and E. coli. Figure produced in QGIS (QGIS,2024).

Of the 3,388 complete water quality tests surveying NO3, 207 (6.11%) exceeded the WHO threshold of 50mg/L(WHO, 2017) with the average NO3level of 3.1mg/L. There were 322 cases of contamination over 10mg/L, exceeding historic Malawi Standards guidelines (Pullanikkatil et al., 2015; MBS, 2017) and 212 cases exceeding 45mg/L, current Malawi Standards guidelines (Chidya et al., 2016; MBS, 3017). Overall, of the 2,418 MICS water quality surveys, 1,383 (57.2%) water-points had E.coli contamination surpassing WHO guidelines of 0 E.coli /100ml (NSO, 2021). 361 (14.9%) water-points had 100 or more E.coli/100ml.

3.2 Multiple linear regression contamination model selection

There was high multi-collinearity between population density and (pit) latrine density for all models. To meet the assumption of collinearity, one of the variables with high multi-collinearity (latrines and population) was removed. Following removal all VIF values were below 3 and met the assumption of collinearity. For each contamination model, models were produced for all variables excluding latrines and another model with all variables excluding population. Model fit was evaluated and summarized in Table 2. The model with the highest model accuracy was selected as the GLMM model used for further analysis.

For nitrate above 50mg/L and high *E.coli* contamination (≥ 100 *E.coli*/100ml), the model including latrine density as a predictor variable had higher accuracy than the model including population density. For *E. coli* presence (>0 *E.coli*/100ml) the model with population density as a predictor variable resulted in higher accuracy than the model with latrine density. All diagnostic plots and assumptions for the selected GLMM for each contaminant are provided in the Supplementary Information.

Table 2: Model performance for the contaminant models containing either latrine density or population density. Multiple metrics are shown. The model which provided best performance for each contaminant model is highlighted in bold. Core variables are: Anthropogenic Biome, Cropping Intensity, Fertiliser, Flooding, Manure, Pit-Latrine Density, WRU Pit-latrine density, Livestock, Open

Defecation, Poverty and Precipitation. McFadden Pseudo R^2 *values between 0.2-0.4 are considered an excellent fit.*

Contaminant model	Variables included in model	McFadden Pseudo R^2	Accuracy	Precision	Sensitivity	Specificity
≥ 50mg NO_3/L	Core Variables + Population	0.306	**70.92%**	3.209%	50.00%	**71.32%**
	Core Variables + Latrines	**0.329**	68.23%	**3.421%**	**54.17%**	68.52%
>0 *E.coli*/100ml	**Core Variables + Flush Latrine + Population**	**0. 0790**	**57.98%**	72.17%	**57.58%**	58.72%
	Core Variables + Flush Latrine + Latrines	0. 0775	56.02%	**75.35%**	47.93%	**71.00%**
	Core Variables + Flush Latrine + Population	0. 2075	**80.97%**	**41.67%**	57.25%	**85.31%**

≥ 100 *E.coli*/100ml	**Core Variables + Flush Latrine + Latrines**	**0. 2404**	78.52%	39.07%	**61.31%**	81.70%

3.3 NO_3 contamination multiple linear regression model

The binomial GLMM (with no fixed effects) for NO_3 contamination had good model performance with a McFadden Pseudo R^2 value of 0.329 (considered excellent fit), 70.9% overall model accuracy, 50% sensitivity and 71.3% specificity.

Predictor variable estimates are presented in Figure 3. Precipitation was the significant predictor variable with the highest estimate, with areas with higher precipitation reporting a lower incidence of high NO_3 contamination (≥ 50mg NO_3/L). A similar effect was also observed for flooding, areas with high flooding had a lower chance of having high NO_3. Anthropogenic factors also influenced NO_3 levels. Areas with higher anthropogenic biome, a measure of ‘wildness’, with high anthropogenic biome values being further away from both urbanised areas and intensive cropping, had more NO_3 contamination. This was also seen in that cropping intensity, latrine density, and livestock density were negatively correlated with the presence of high NO_3 contamination. Water points in areas with high poverty were also less likely to report high nitrate levels. Areas with a high catchment level density of pit-latrine users (WRU Latrine User Density) had more waterpoints with nitrate values exceeding safe limits. This was the only factor to have a significant positive correlation with the presence of high NO_3 contamination.

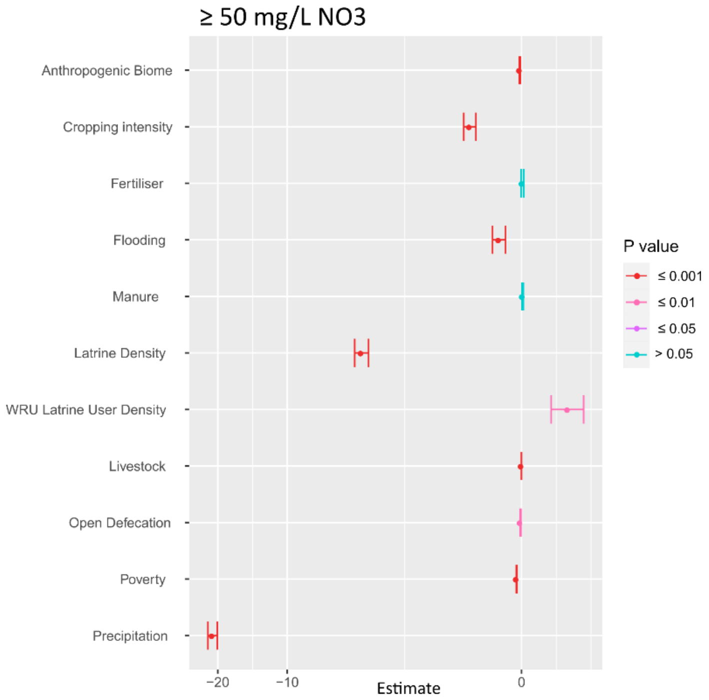


Figure 3: GLMM model for the presence of high nitrate contamination (≥ 50mg NO_3/L) of water-points. Significant variables are highlighted in red and pink. Non-significant variables are shown in blue.

3.4 E. coli contamination multiple linear regression model

Two binomial GLMM (fixed effects of date and water source) were produced for *E.coli* contamination. The results are summarised in Figure 4. For the presence of *E.coli* contamination (>0 *E.coli* / 100ml), the GLMM model had a Macfadden R^2 value of 0.08 and 58.0% accuracy indicating moderate performance. The area being impacted by 2019 flooding and the density of people practising open defecation were significantly correlated with an increased presence of *E.coli* contamination. Areas with high flush toilet usage were significantly less likely to have some *E.coli* contamination.

For high *E.coli* contamination (≥ 100 *E.coli*/100ml), the model had an 'excellent fit' with a Macfadden R^2 of 0.24 and a high accuracy of 78.5%. Precipitation and pit-latrine density significantly resulted in an increased risk of high *E.coli* contamination. Livestock density and the area being impacted by 2019 flooding were significantly negative drivers of high *E.coli.*

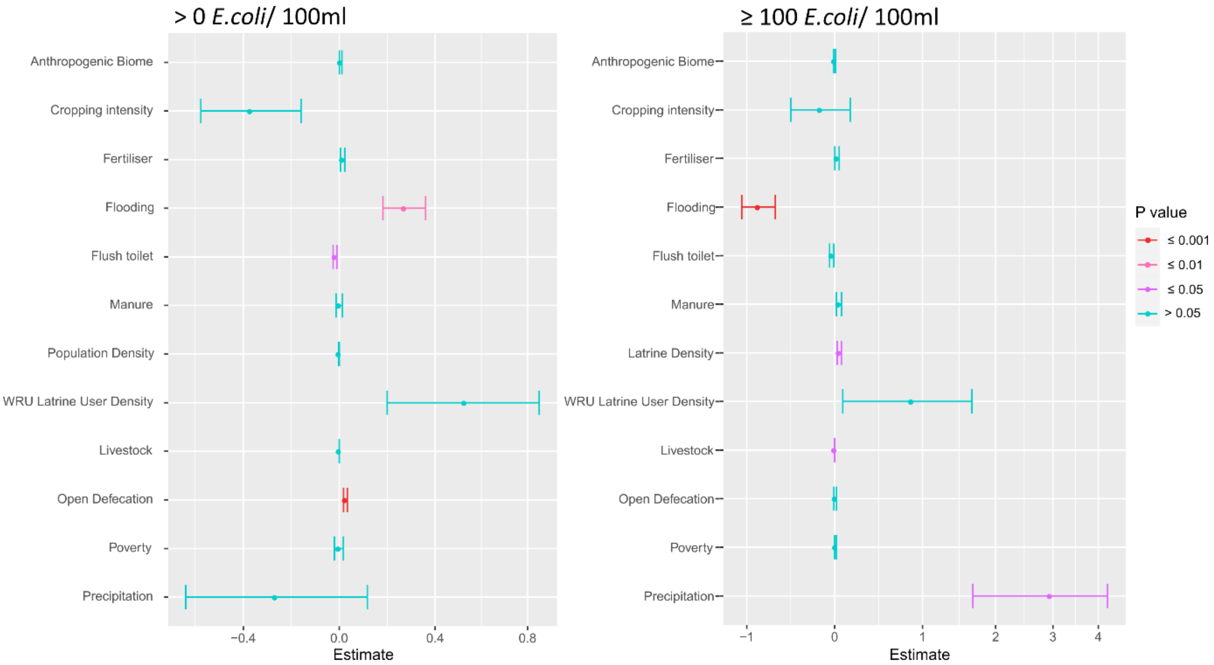


Figure 4: Fixed effect GLMM models for the presence of any (>0 E coli/ 100ml) and high contamination (≥ 100 E.coli/ 100ml) E.coli of water-points. Significant variables are highlighted in red and pink. Non-significant variables are shown in blue.

3.5 Random forest prediction of contamination

A regression RF model for NO_3 contamination was generated for continuous data of NO_3 levels. Overall, the RF model had good model performance with a Root Mean Squared Error (RMSE) of 10.6 and a R^2 fit of 0.87. The plot of predicted vs measured nitrate contamination is shown in the Supplementary Information Figure 8. Overall, the model underestimated nitrate contamination, particularly in cases where there was very high contamination.

As *E.coli* contamination was predicted as a binary variable (whether contamination was above set thresholds) the *E.coli* contamination RF model was evaluated by confusion matrix model performance metrics, (Eq 1-4). For predictions of where there was some *E.coli* contamination, the random forest model had an average error rate of 30.0% (70.0% accuracy). The model performed better than the multiple linear regression model for all metrics.

For high *E.coli* contamination (≥ 100 E.coli/100ml) the model had a 19% error rate (81% accuracy). The model performed better than the multiple linear regression model for accuracy and specificity, as it performed well at identifying areas without high *E.coli* contamination.

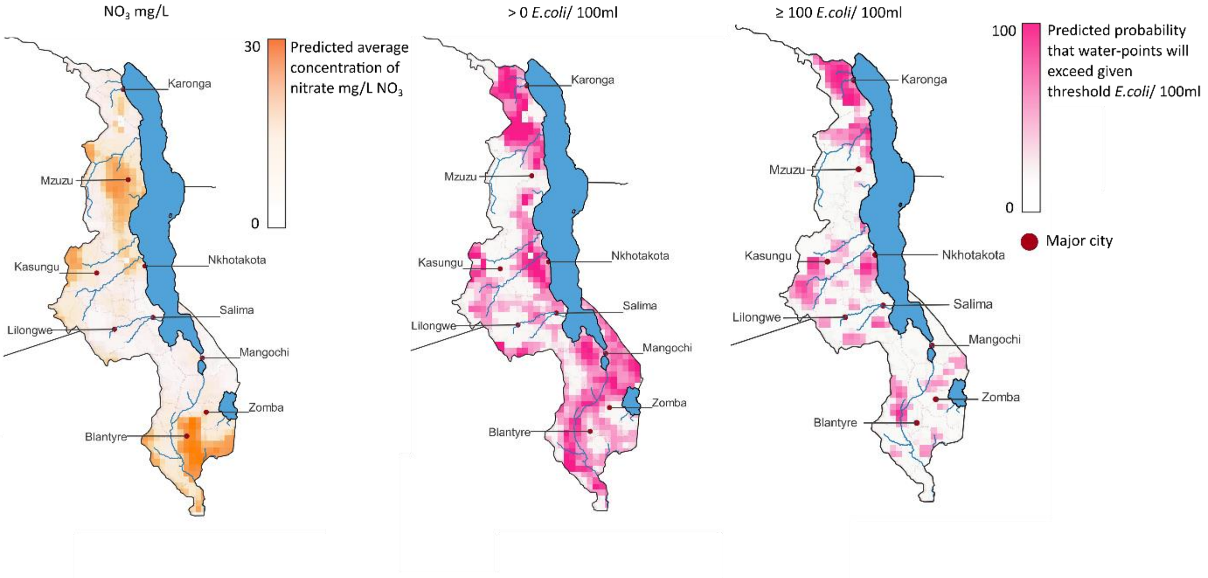


Figure 5: Predicted contamination from random forest models of NO_3 and E. coli. NO_3 contamination was modelled as a continuous response variable with the predicted amount of nitrate contamination given as NO_3 mg/L. The model underpredicted some of the areas with highest contamination but had overall good performance with an R^2 of 0.87. Areas with predicted high levels of nitrate contamination were surrounding the cities of Blantyre and Mzuzu (Water Resource Areas 1 and 7). The presence of > 0 E.coli/ 100ml and ≥ 100 E.coli/100ml were modelled as binary variables with discrete response variables. The model of whether a given water-point had > 0 E.coli/ 100ml had 70% accuracy. Rural areas as well as areas in the north surrounding Karonga, along the Shire River, and peri-urban areas outside of the major cities were predicted to have high levels of some E. coli contamination. The model of whether a water-point had ≥ 100 E.coli/100ml had 81% accuracy. Areas in the north, surrounding Karonga as well as areas close to major cities were predicted to have high levels of high E.coli contamination. Figure produced in QGIS (QGIS, 2024)

However, the model failed to identify some of the cases of high contamination and performed worse for precision and sensitivity. Confusion matrices for both *E.coli* models are provided Supplementary Information Tables 7 and 9. The spatial distribution of areas of predicted contamination are summarised in Figure 5.

Figure 6 shows Shapley values, showing the contribution of each feature within the random forest model produced for each contaminant considered. For all cases, flooding was the feature with least contribution. For NO_3 and high *E.coli* contamination (≥ 100 E.coli/100ml), sanitation related variables were the two variables with the highest contributions (WRU latrine user density and latrine density for NO_3 and flush toilet and open defecation for *E.coli*). For *E.coli* presence (> 0 E.coli/ 100ml), cropping and anthropogenic biome had the highest contribution.

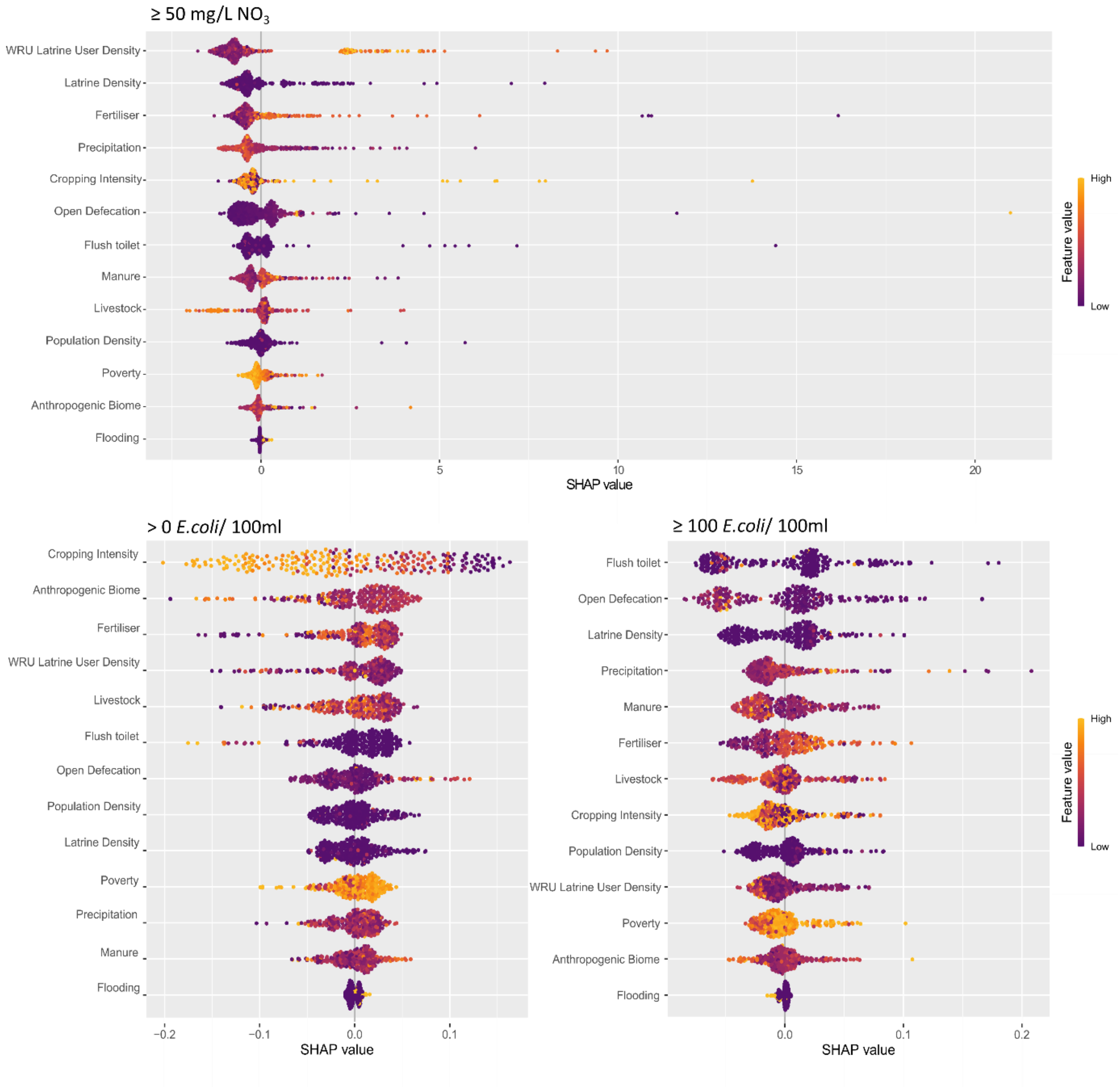


Figure 6: Shapley values of variables within the Random Forest Regression model. The colour gives feature values. Features are ordered by the feature's mean Shapley value (an indicator of feature importance).

3.6 Pilot Isotope Study

Stable isotope hydrology was introduced in Malawi by the IAEA to enhance monitoring and management of water resources in Malawi. This pilot study was part of a wider application of stable isotopes across the country (Banda et al., 2019; Banda et al., 2021). Stable isotopes of nitrate have the potential to validate the sources of nitrogen compounds in the water environment (Minet et al. 2017). Of the 15 groundwater and surface water samples collected within the pilot, 40% (6) had concentrations of NO_3^-–N at or above 0.1mg/l concentration which warrants measurement of δ^{15}N-NO_3^- and δ^{18}O-NO_3^-. Samples were analysed in triplicate, the δ^{15}N-NO_3^- ranged from -1.9 (±1.7) to 27.7 (±1.3)‰ with a mean of 11.4 (±0.6), while the δ^{18}O-NO_3^- ranged from 0.0 (±1.0) to 16.3 (±0.3)‰, with a mean of 8.6 (±1), Table 3.

Table 3: Measured δ15N-NO3 and δ18O-NO3 signatures for selected groundwater and surface water sources

Number	Type	NO_3 (ppm)	⍰^{15}N	+/-	⍰^{18}O	+/-
1	Groundwater	6.5	6.1	0.2	3.5	1.3
2	Groundwater	0.6	27.7	1.3	16.3	0.3
3	Surface Water	0.1	-1.9	1.7	0.0	1.0
4	Groundwater	2.6	4.3	0.1	4.1	2.2
5	Groundwater	1.5	14.4	0.2	15.1	0.1
6	Surface Water	1.5	17.6	0.2	12.4	0.9

While the dataset is limited, the results do indicate the most likely source of nitrate in surface water and groundwater originated as oxidised ammonia (NH_4^+), Figure 7. The results also suggest that manure or human waste is a likely source of the ammonia together predicted trends due to denitrification (Kendall et al., 2007), Figure 7. The dataset is not sufficient to track source terms and dynaMICS (Minet et al., 2017), but it does support the findings of this paper which points to pit-latrine derived nitrate in groundwater as a concern, and clearly show a strong potential for further study together with geochemical indicators to validate the predictions put forward in this paper.

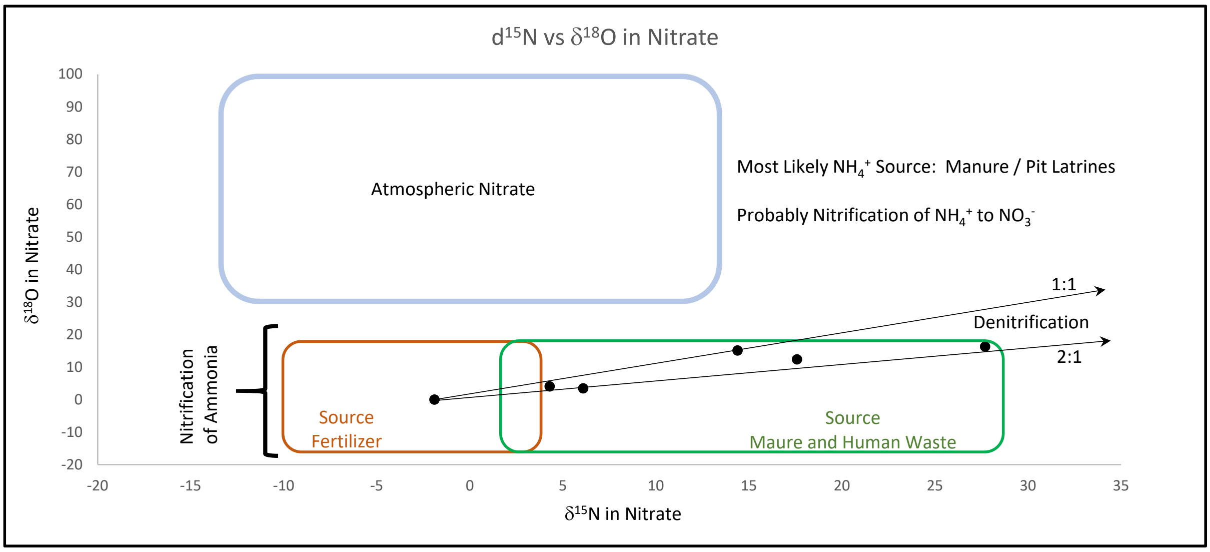


Figure 7: Results of $\delta^{15}N\text{-}NO_3^-$ and $\delta^{18}O\text{-}NO_3^-$ plotted with the likely source of N species and trends added after Kendall et al. 2007.

4. Discussion

4.1. Sources of contamination

Almost 80% of the population of Malawi access water from groundwater sources (boreholes/tubewells, wells, and springs) (NSO, 2021) making management of groundwater quality critical for ensuring safe drinking water. Protecting groundwater from the growing threat of anthropogenic contaminants is therefore essential. High levels of contamination pose a challenge to public health and sustainable development, particularly holding back Malawi's capacity to reach SDG6, specifically SDG6.1 'safe drinking water for all' (UN General Assembly, 2015).

The contaminants NO_3 and *E.coli* are of concern for Malawi's water provision. Nitrate pollution is a public health concern and has been a growing concern in water quality in Malawi (Chidya et al., 2016; Chimphamba and Phiri, 2014; Nkwanda et al., 2021; Pullanikkatil et al., 2015; von Hellens, 2013.,) with high levels reported in both surface water (Nkwanda et al., 2021; Pullanikkatil et al., 2015; Sajidu et al., 2007) and groundwater sources (Chidya et al., 2016; Chimphamba and Phiri, 2014; von Hellens, 2013.). High groundwater nitrate pollution has been linked to contamination from sanitation sources, both within Malawi (von Hellens, 2013.; Back et al., 2018.) and beyond (Templeton et al., 2015; Ouedraogo et al., 2019; Rahman et al., 2021). Increasing loading of nitrate to groundwater is a particular concern for safeguarding water quality; nitrate does not undergo reduction in aerobic environments, and therefore remains in groundwater for extended periods. It also means nitrate can be transported over large distances in groundwater making sources of contamination hard to trace (Canter, 1996).

Catchment level density of pit-latrine use (modelled density of pit-latrine users within WRU) was identified as the only significant positive driver of high nitrate levels. This suggests that catchment level sanitation considerations are important in managing nitrate groundwater contamination (Carter, 1996; Hinton et al., *in review*). Conversely, areas with high densities of pit-latrines themselves were less likely to have high levels of nitrate groundwater contamination. High pit-latrine density is mostly found in areas of high population density, the high concentrations of leachate will more likely result in anaerobic conditions in groundwater, therefore not resulting in high levels of nitrate. Pit-latrine related variables (WRU pit-latrine user density and pit-latrine density) were also identified as the features with the greatest contributions within the continuous random forest regression (RFR) model of nitrate contamination (R^2 0.87). As in the case of the GLMM, high pit-latrine users per WRU density increased the likelihood of high nitrate in groundwater whilst higher pit-latrine densities themselves were negatively correlated with nitrate contamination within the model, although care should be taken in interpretation of RF importance.

Collectively considering these results, our findings strongly support previous examinations of nitrate contamination sources identifying sanitation sources as key drivers of nitrate pollution (Chidya et al., 2016; Chimphamba and Phiri, 2014.; Ouedraogo et al., 2019; von Hellens, 2013). Ouedraogo *et al.,* 2019, found that population density was a better predictor of pan-African nitrate levels level than fertilizer, suggesting that the lack of sanitation in major part of the African continent may be the reason for population density resulting in greater nitrate contamination (Ouedraogo et al., 2019). We build upon this inference, suggesting that pit-latrines themselves, more specifically pit-latrine density on a catchment/ sub-catchment scale, is a major source of groundwater nitrate contamination. The relationship between population density / pit latrines and nitrate in groundwater was validated via the results of the pilot study of $\delta^{15}N\text{-}NO_3^-$ and $\delta^{18}O\text{-}NO_3^-$ in groundwater and surface water samples that indicates manure and/or pit-latrines present the major source of nitrate contamination. A nation-wide study that monitors nitrate and stable isotopes is recommended to monitor the projected growth of pit-latrine usage within Malawi (Hinton et al., 2023) and consequent growing risk of high densities of faecal waste loading (Hinton et al., *in review*).

E.coli contamination is a significant barrier to achieving access to safe drinking water within Malawi (NSO, 2021) and a public health concern. Nationally, 57.2% of groundwater drinking water sources (tube wells/ boreholes, dug wells, and springs) were found to not meet WHO guidelines for safe drinking water (having no *E.coli*). More concerning were the 14.9% of groundwater drinking water sources that show exceptionally high levels of *E.coli* contamination with 100 or more *E.coli* in a 100ml sample. To evaluate drivers and provide spatial prediction of *E.coli* contamination in groundwater drinking water supplies, we applied categorical GLMM and RF models. We considered two cases of *E.coli* contamination, evaluating both the presence of any *E.coli* in drinking water (exceeding WHO guidelines) and another model evaluating very high levels of *E.coli* contamination (≥ 100 *E.coli/*100ml). Both cases were modelled as binary variables of the presence/ absence of any/very high *E.coli* contamination.

For the presence of both any *E.coli* contamination and high *E.coli* contamination, sanitation related variables were identified as critical drivers. A high density of people practising open defecation was a significant positive driver of the presence of any *E.coli* contamination whilst flush toilet usage was negatively correlated with the presence of any *E.coli* within the GLMM model. In areas where there is a high level of open defecation, environmental contamination because of open defecation may result in contamination of groundwater drinking water sources.

Environmental contamination by open defecation can result in contamination of groundwater water-points through contaminated surface water (Rivett et al., 2022). Water-point contamination from contaminated surface runoff alongside an elevated groundwater table promoting increased pit-latrine groundwater contamination has also been reported during flooding (Rivett et al., 2022). The geographic areas most impacted by heavy flooding in 2019 typically in the south of the country near the Shire River (approximately 1 year prior to water quality testing), were more likely to have evidence of *E.coli* contamination. Conversely, areas impacted by 2019 flooding, were significantly less likely to have very high *E.coli* contamination. This may be due to the flooding areas having been impacted by floods about a year prior to the water quality tests being conducted and cases of exceptionally high *E.coli* may have undergone intervention over this time.

These findings underline the importance of community wide approaches in ending open defecation to preventing drinking water contamination (Hinton et al., *in review*). Unless safe sanitation for all is provided (as outlined in SDG6.2), safe drinking water provision may be undermined. Water-points which are damaged or partially functional are more likely vulnerable to contamination from contaminated surface water (Rivett et al., 2022), this is a particular concern in Malawi where 40% of boreholes are partially or completely non-functional and maintenance of water-points is highly limited (Kalin et al., 2019; Kalin et al. 2022). Combatting groundwater *E.coli* contamination should consider not only sustainable progress towards ending open defecation but also ensuring improved borehole maintenance and functionality (Kalin et al., 2019) promoting community-led solutions to borehole functionality in conjunction with ending open defecation (Hinton et al., 2021).

4.2 Predicted Spatial distribution of contamination

Prediction of distribution of nitrate and E.coli contamination using RF models enabled greater spatial investigation of areas at high risk of contamination. Spatial prediction of areas susceptible to nitrate contamination identified water-points within water resource areas (WRA)

1 and 7, around the cities of Mzuzu and Blantyre, to be more likely to have high nitrate contamination. These areas have a high density of pit-latrine users within these catchments and also have limited precipitation. Spatial prediction of areas with any *E.coli* contamination (70% accuracy) predicted that areas with any *E.coli* contamination were more likely to be in rural or peri-urban areas with a high density of people practicing open defecation and susceptible to flooding. Spatial prediction of the highest contamination cases, where there were 100 or more *E.coli* per 100ml, had 81% accuracy. Cases of high contamination were mostly predicted in densely populated, non-urban areas with high pit-latrine density and high precipitation, typically in peri-urban towns or along roads.

4.3 Study limitations

Samples used for statistical analysis of nitrate contamination were gathered by the Government of Malawi when new boreholes were established. Overall, a national dataset of 2,993 boreholes was analysed. To gather such an extensive dataset, samples collected over a 22-year period were analysed, although most samples were collected after 2015. For statistical analyses, spatial rasters of given predictor variables were used, these were typically circa 2020, although ranged from circa 2010. Selecting only samples taken within a smaller time window resulted in smaller sample sizes as well as samples that may not be nationally representative thereby reducing the statistical power of the analysis. This limitation was deemed acceptable considering that spatial patterns of predictor variables were consistent over time. Future campaigns gathering national, extensive samples of nitrate contamination, as was seen for microbial contamination in the 2019/20 MICS survey, should be prioritised to enable more detailed analysis.

The level of *E.coli* contamination was provided as a binary variable for samples up to an including 100 *E.coli* /100ml, however, when contamination was greater than 100 *E.coli* /100ml, this was marked as a binary measure. As such, for the purposes of this analysis, *E.coli* contamination was considered as a binary (presence of any *E.coli* contamination, and 100 or more *E.coli* /100ml). This limitation was a result of the sampling method used for which it is hard to count more than 100 *E.coli* within a sample. This restricted analysis to binary methods or to only considering cases below 100 *E.coli* /100ml. As this work was particularly interested in high contamination, binary analysis was completed. Further insights could be facilitated, including providing a better prediction of the level of *E.coli* contamination, through analyses with continuous variables.

We also present a pilot study of isotopic analysis of nitrate contamination sources for surface water and groundwater in the Linthipe river sub-catchment (rural and urban). Whilst the results do indicate nitrate sources from manure and domestic wastewater, only 15 samples underwent isotopic analysis (due to analytical limitations) and limited resources, with the isotopic analysis conducted at the IAEA in Vienna, Austria. Of those samples, only 6 had nitrate levels with sufficient nitrate to conduct the analysis. The Linthipe river has a high base-flow index (river flow dependant on groundwater discharge (Kelly et al. 2020)) and as such 2 of the 6 samples were surface water and was considered relevant for inclusion due to the high connectivity observed in Malawi between groundwater and surface water (Kelly et al.,2020). A large-scale national study of isotope hydrology and nitrogen compounds in surface water and groundwater is highly recommended.

4.4 Policy recommendations and future work

This study supports previous findings within Malawi, and on a continental scale, that sanitation infrastructure is a critical consideration for both nitrate (Templeton et al., 2015.; Ouedraogo et al., 2019; Rahman et al., 2021) and microbial (Pritchard et al., 2007; 2008) groundwater contamination. The study emphasises the importance of community wide improvements in sanitation access as open defecation and poor sanitation infrastructure can result in contamination of community-based water resources. This echoes the ethos of programmes such as Community Led Total Sanitation (CLTS) which emphasise the environmental health component of enhanced sanitation provision (Chamber and Kar, 2008). However, whilst these initiatives push for community level ends to open defecation, this work highlights the importance of community wide changes in sanitation not only focusing on eliminating open defecation but also on evaluating appropriate pit-latrine usage and management. *Community level ending of open defecation is important but environmental health perspectives of inappropriate sanitation should also be emphasised.*

This work highlights a paradox in Malawi's progress in sanitation and water; open defecation must be eliminated to improve sanitation and water access but pit-latrines, which often form 'starter sanitation' (UNICEF, 2018) may cause contamination themselves unless appropriately managed. *Appropriate pit-latrine use will be important in ensuring an end to open defecation without resulting in widespread water contamination.* To ensure progress in both spheres of water and sanitation, enhanced policy frameworks to foster cooperation between stakeholders should be promoted. Sanitation infrastructure development must consider groundwater contamination consequences. Critically, this involves guiding long-term investment into higher quality waste management that minimizes contamination considering future projections of high population growth and increasing pit-latrine usage (Hinton et al., *in review*).

Our findings support initiatives to target water quality monitoring in areas of concern. Further expansion of isotope analysis may facilitate tracing of groundwater contaminant sources and develop evidence for source contamination management. Further understanding of contamination, both nitrate and microbial contamination, is needed to guide intervention. Understanding sanitation use within this will be critical (pit-latrine density was a better predictor of contamination of nitrate and high *E.coli* contamination than population density). Future work and modelling efforts should account for addition factors such as soil type (He et al., 2022), and localised groundwater dynaMICS to enhance understanding of areas at high risk of contamination.

5. Conclusion

We apply a mixed method approach to identify drivers of microbial and nitrate contamination of groundwater drinking sources in Malawi. A pilot application of isotope hydrology was used to validate likely sources of nitrate contamination of groundwater. Statistical analysis was used to further enhance understanding of sources of nitrate contamination with catchment level pit-latrine usage identified as a significant driver of areas with high nitrate groundwater contamination. These findings support previous analyses of groundwater in Malawi and across Africa of sanitation sources being a major driver of groundwater nitrate contamination (Templeton et al., 2015.; Ouedraogo et al., 2019; Rahman et al., 2021). Pit-latrines were noted as a specific concern, highlighting the need for understanding of how sanitation derived contamination occurs. The results raise concerns for future groundwater contamination with projected increases of pit-latrine usage in Malawi driven by a move to end open defecation alongside high population growth (Hinton et al., *in review*).

Sanitation related factors were significant considerations for microbial groundwater contamination. The density of open defecation was found to be significant driver in cases of any *E.coli* contamination whilst in areas with very high *E.coli* contamination, pit-latrines are most likely the significant source of contamination. Policy and research efforts need to navigate how appropriate sanitation can be provided to ensure an end to open defecation without coming at the cost of groundwater quality. We also found that flooding risk in an important predictor of microbial borehole contamination, however, more research with higher quality flood risk predictive data would enhance understanding of the future risks of water-point contamination due to climate-change enhanced flooding.

Acknowledgements

This work was conducted as part of a Scottish Government funded joint PhD studentship under the Climate Justice Fund Water Futures Program. Georeferenced *E.coli* data was provided from the Malawi 2019/20 MICS Survey by UNICEF Malawi . Nitrate borehole water quality samples were provided by the Government of Malawi, Ministry of Water and Sanitation. The pilot nitrate isotope tracing work was conducted as part of an International Atomic Energy Agency (IAEA) national project (MWL-7002 TC project).

6. Supplementary Information

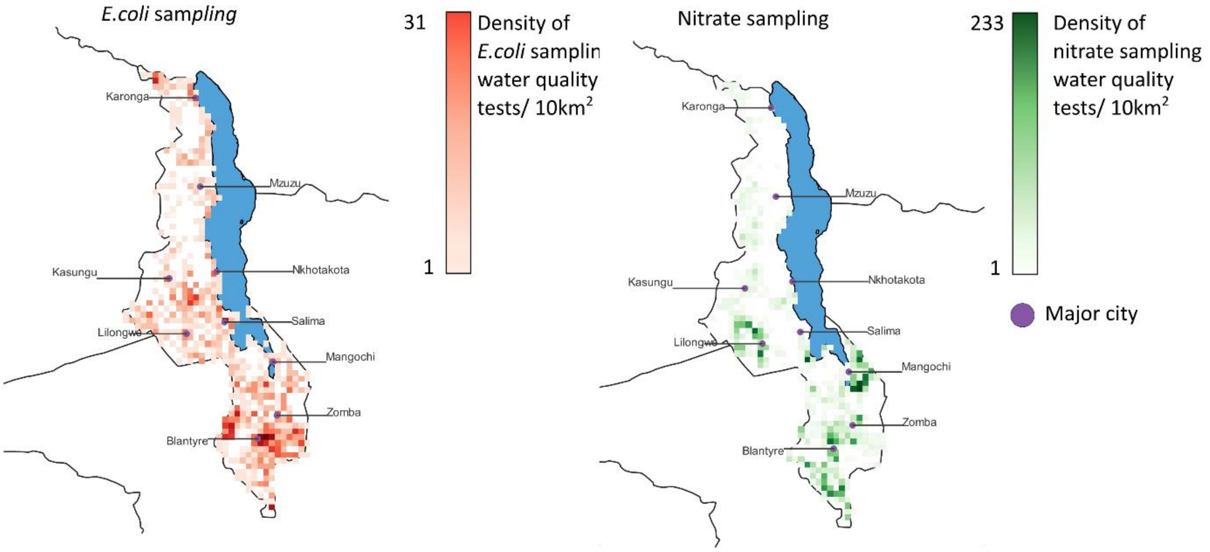
6.1 Water quality sampling

6.1.1 Groundwater drinking water sources E.coli MICS survey

Supplementary Information Table 1: Sources of groundwater drinking water samples which underwent water quality testing in the UNICEF 2019/20 MICS survey.

Variable	Cases
Tube well/ borehole	1,967
Dug well (protected)	155
Dug well (unprotected)	203
Spring (protected)	15
Spring (unprotected)	51

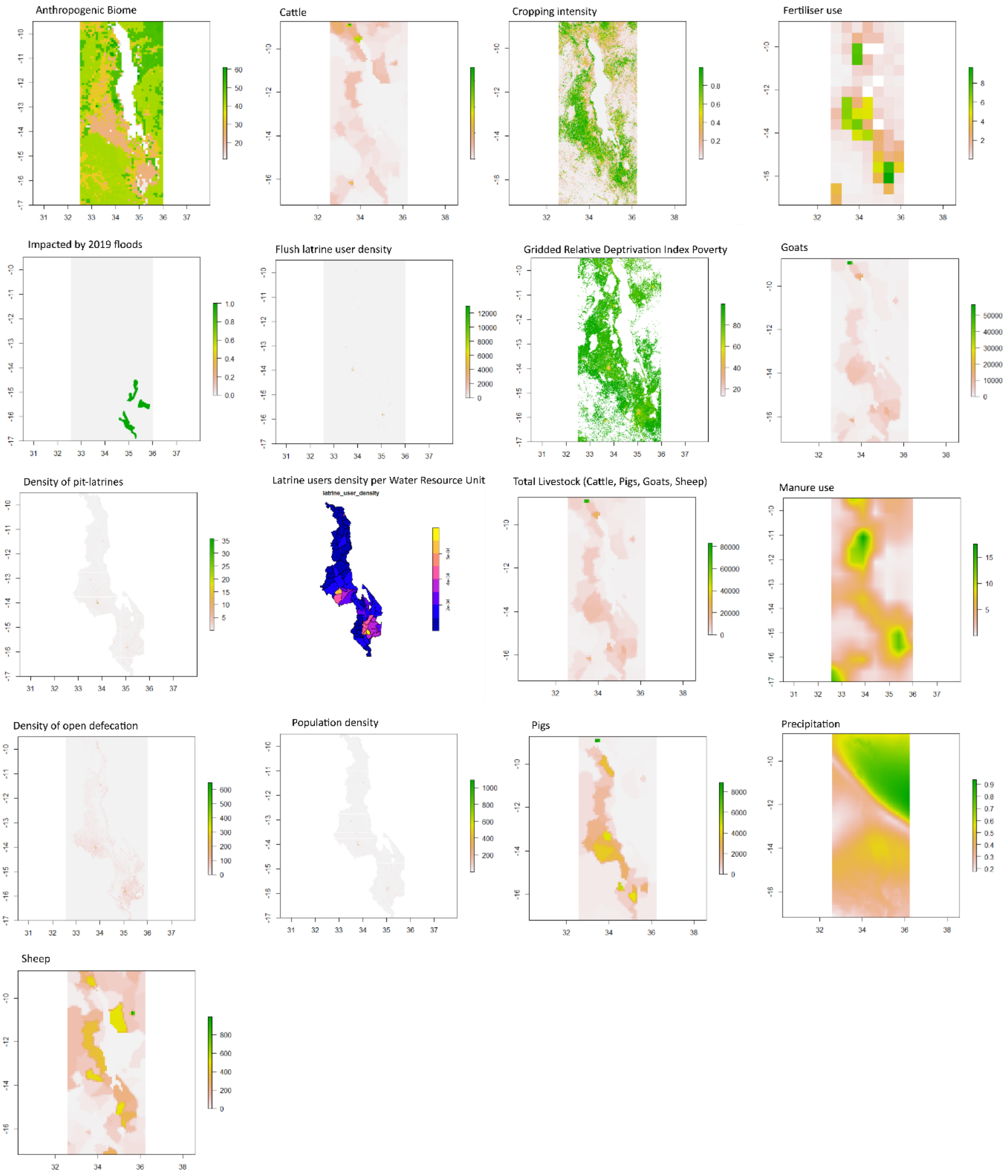
6.1.2 Sampling intensity E.coli and Nitrate



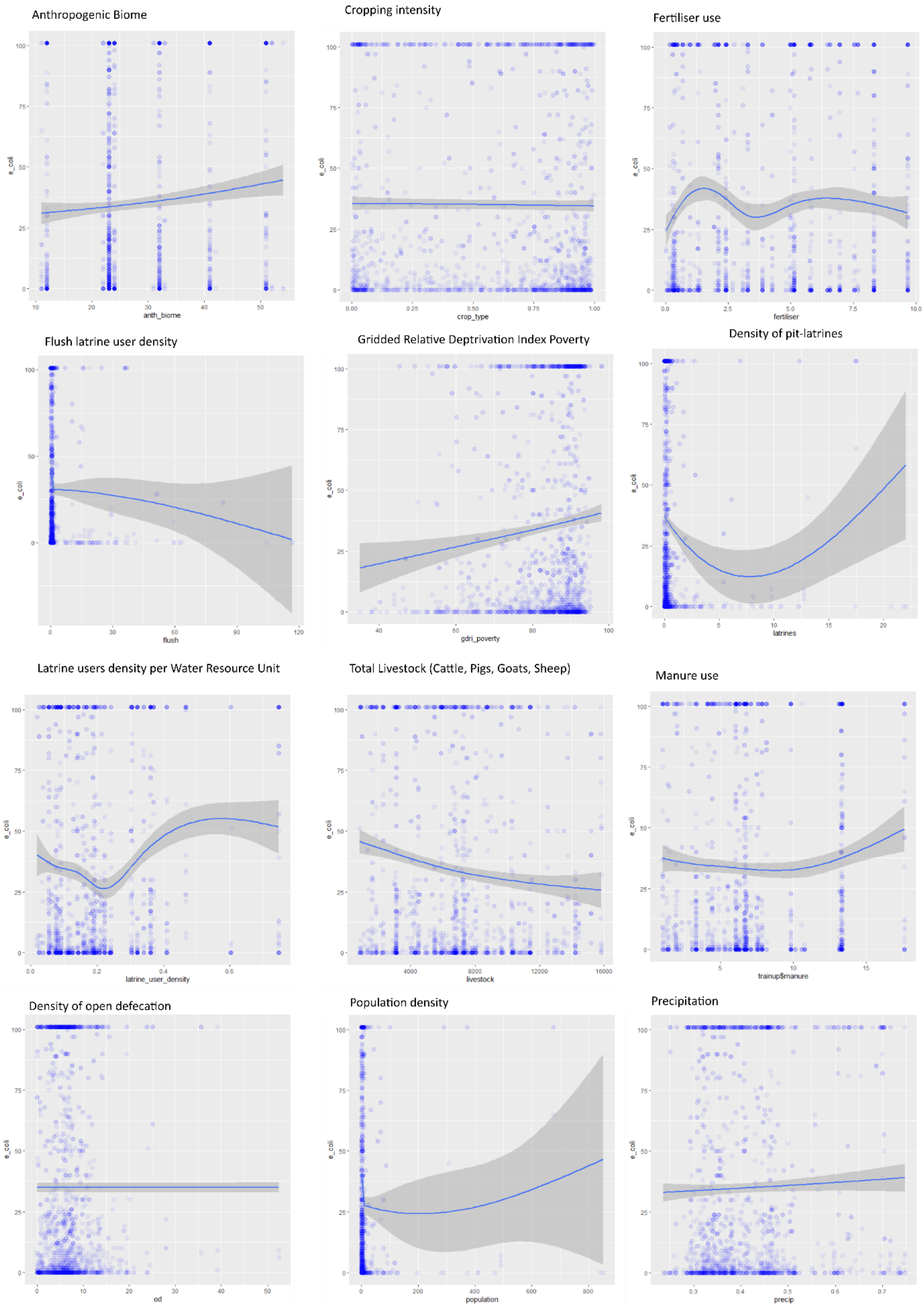
Supplementary Information Figure 1: Sampling intensity of UNICEF MICS 2019/20 survey (assessing E. coli contamination) and Government of Malawi borehole water quality assessments (assessing nitrate contamination.)

6.2 Statistical analysis predictor variables

6.2.1 Predictor variables spatial plots



Supplementary Information Figure 3: Spatial plots of predictor variables for statistical analysis.


Anthropogenic Biome

Cropping intensity

Fertiliser use

Flush latrine user density

Gridded Relative Deptrivation Index Poverty

Density of pit-latrines

Latrine users density per Water Resource Unit

Total Livestock (Cattle, Pigs, Goats, Sheep)

Manure use

Density of open defecation

Population density

Precipitation

Supplementary Information Figure 4: Relationship between predictor variables and measured E.coli contamination at groundwater sourced water-points

6.2.2 E.coli and predictor variables

6.3 Multiple linear regression model diagnostic plots

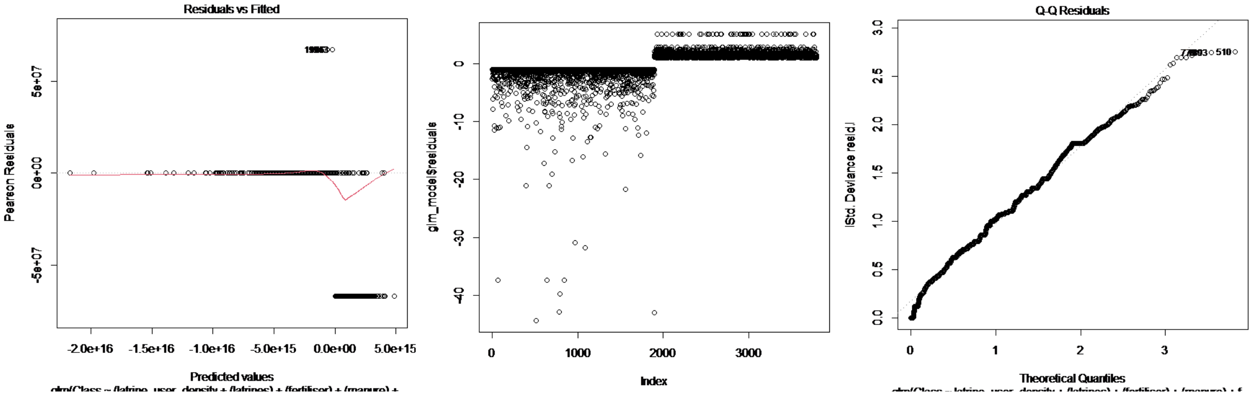
6.3.1 Nitrate contamination GLMM diagnostic plots

Supplementary Information Table 2: Variable inflation factor (VIF) for multiple linear regression model of high NO_3 contamination prior to removal of flush latrines. There is high VIF of the variables open defecation and flush latrine usage. One variable was selected out of these for removal (flush latrine usage).

Variable	VIF Value
WRU latrine user density	1.411885
Latrine density	2.110109
Fertiliser	1.355609
Manure	1.387313
Flooding	1.969239
Precipitation	1.914630
Cropping intensity	1.479037
Anthropogenic Biome	1.815807
GDRI poverty	2.295915
Open defecation	18.463178
Flush toilet	15.792912
Livestock	1.718324

Supplementary Information Table 3: Variable inflation factor (VIF) for multiple linear regression model of high NO_3 contamination following removal of flush latrines. All VIF values are below 5 and meet the assumptions of multicollinearity.

Variable	VIF Value
WRU latrine user density	1.372181
Latrine density	2.122478
Fertiliser	1.345011
Manure	1.378575
Flooding	1.790915
Precipitation	1.566339
Cropping intensity	1.446776
Anthropogenic Biome	1.798316
GDRI poverty	2.255401
Open defecation	1.286738
Livestock	1.768900

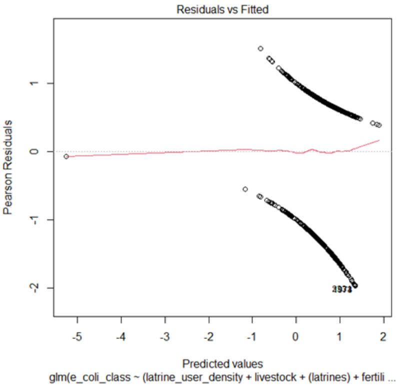


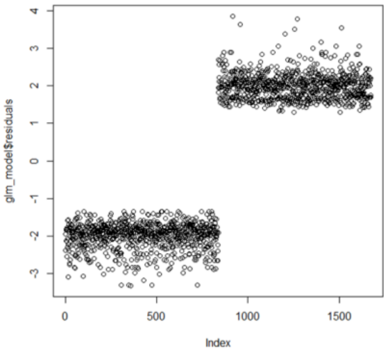
Supplementary Information Figure 5: Diagnostic plots for binary GLMM with no fixed effects of high NO_3 contamination (no flush toilet variable). Plots are a residuals vs fitted plot (verify linearity), residuals plot (confirm absence of significant tracking of residuals therefore meeting independence assumption) and Q-Q plot (evaluate non-normal deviance residuals and verify that the model meets the assumption of normal response distribution). The diagnostic plots confirm that the model meets assumptions of linearity, response distribution and independence.

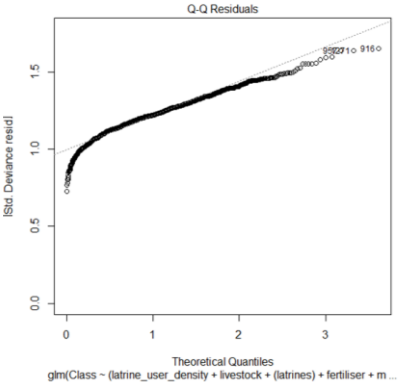
6.3.2 E. coli presence GLMM diagnostic plots

Supplementary Information Table 4: Variable inflation factor (VIF) for multiple linear regression model of E.coli presence. All VIF values are below 5 and meet the assumptions of multicollinearity.

Variable	VIF Value
WRU latrine user density	1.163910
Latrine density	1.396028
Fertiliser	1.361694
Manure	1.157079
Flooding	1.068536
Precipitation	1.291955
Cropping intensity	1.110220
Anthropogenic Biome	1.279427
GDRI poverty	1.585014
Open defecation	1.201761
Flush toilet	1.212228
Livestock	1.311040





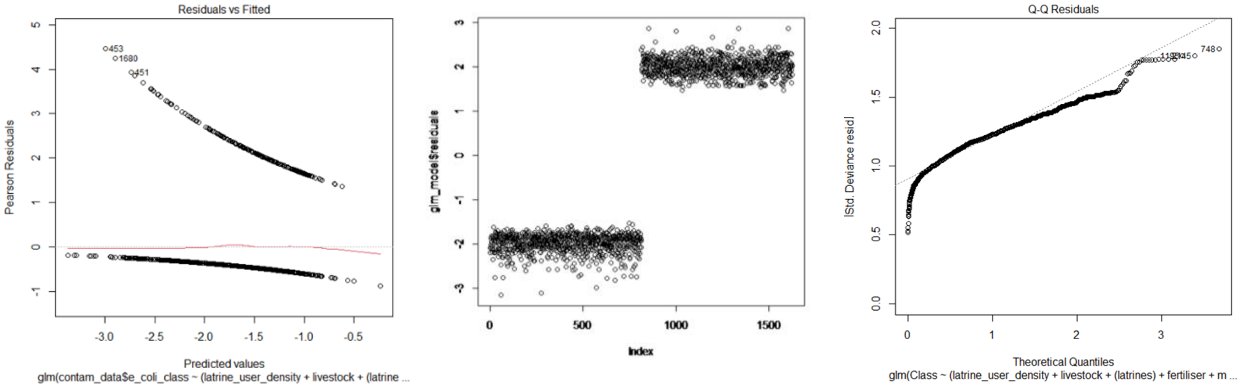


6.3.3 High E. coli GLMM diagnostic plots

Supplementary Information Table 5: Variable inflation factor (VIF) for multiple linear regression model of high E. coli (≥100 E. coli/100ml). All VIF values are below 5 and meet the assumptions of multicollinearity.

Supplementary Information Figure 6: Diagnostic plots for binary GLMM with fixed effects of E. coli presence contamination. Plots are a residuals vs fitted plot (verify linearity), residuals plot (confirm absence of significant tracking of residuals therefore meeting independence assumption) and Q-Q plot (evaluate non-normal deviance residuals and verify that the model meets the assumption of normal response distribution). The diagnostic plots confirm that the model meets assumptions of linearity, response distribution and independence.

Variable	VIF Value
WRU latrine user density	1.207102
Latrine density	1.594025
Fertiliser	1.326882
Manure	1.143947
Flooding	1.072548
Precipitation	1.269720
Cropping intensity	1.151303
Anthropogenic Biome	1.316766
GDRI poverty	1.902617
Open defecation	1.171533
Flush toilet	1.270481
Livestock	1.311760



Supplementary Information Figure 7: Diagnostic plots for binary GLMM with fixed effects of high E. coli (≥100 E. coli/100ml) contamination. Plots are a residuals vs fitted plot (verify linearity), residuals plot (confirm absence of significant tracking of residuals therefore meeting independence assumption) and Q-Q plot (evaluate non-normal deviance residuals and verify that the model meets the assumption of normal response distribution). The diagnostic plots confirm that the model meets assumptions of linearity, response distribution and independence.

6.4 Multiple linear regression model results

6.4.1 Nitrate contamination GLMM results

Supplementary Information Table 6: Confusion matrix of results of GLMM of nitrate contamination with population used as a predictor variable and not latrines.

	Observed class		
Predicted class		No contamination	Contamination
	No contamination	799	11
	Contaminated	367	13

Supplementary Information Table 7: Confusion matrix of results of GLMM of nitrate contamination with latrines used as a predictor variable and not population.

	Observed class		
Predicted class		No contamination	Contamination
	No contamination	900	12

	Contaminated	362	12

*Supplementary Information Table 8: Results of GLMM of nitrate model with latrines used as predictor variable. Significance codes: *** (0 < p ≤ 0.001); ** (0.001 < p ≤ 0.01); * (0.01 < p ≤ 0.05).*

Variable	Estimate	Std. Error	Z value	p- value
WRU Latrine user density	0.948630	0.354511	2.675886	7.4532e-03 **
Latrines	-4.650477	0.345748	-13.450495	< 2.2e-16 ***
Fertiliser	0.016954	0.023215	0.730314	4.6520e-01
Manure	0.021695	0.014720	1.473810	1.4053e-01
Flood	-0.448362	0.132066	-3.394991	6.8631e-04 ***
Precipitation	-21.069262	0.982419	-21.446309	< 2.2e-16 ***
Cropping intensity	-1.066621	0.135735	-7.858096	3.9002e-15 ***
Anthropogenic biome	-0.032997	0.005919	-5.574703	2.4795e-08 ***
GDRI Poverty	-0.097736	0.006311	-15.486775	< 2.2e-16 ***
Open Defecation	-0.021181	0.008156	-2.596847	9.4084e-03 **
Livestock	-0.000186	0.000019	-9.640484	< 2.2e-16 ***

Log-Likelihood: -1,753.9   Adj. Pseudo R2: 0.328547   BIC: 3,606.6   Squared Cor.: 0.396133

6.4.2 E.coli presence GLMM results

Supplementary Information Table 9: Confusion matrix of results of GLMM of E.coli presence with population used as a predictor variable and not latrines.

	Observed class		
Predicted class		No contamination	Contamination
	No contamination	213	289
	Contaminated	87	266

Supplementary Information Table 10: Confusion matrix of results of GLMM of E.coli presence with latrines used as a predictor variable and not population.

	Observed class		
Predicted class		No contamination	Contamination
	No contamination	175	235

	Contaminated	123	319

*Supplementary Information Table 11: Results of GLMM of E.coli presence with population used as predictor variable. Significance codes: *** (0 < p ≤ 0.001); ** (0.001 < p ≤ 0.01); * (0.01 < p ≤ 0.05).*

Variable	Estimate	Std. Error	Z value	p- value
WRU Latrine user density	0.525878	0.326653	1.6096895	0.10742088
Population	-0.000532	0.000990	-0.537843	0.59068545
Fertiliser	0.014245	0.009052	1.573683	0.11556071
Manure	0.000234	0.013596	0.017198	0.98627844
Flood	0.270780	0.089335	3.031042	0.00243711 **
Precipitation	-0.264800	0.381301	-0.694464	0.48739108
Cropping intensity	-0.369277	0.211252	-1.748037	0.0845755
Anthropogenic biome	0.005929	0.005230	1.133568	0.25697579
GDRI Poverty	-0.001376	0.018547	-0.074214	0.94084016
Open Defecation	0.025732	0.007656	3.361006	0.00077659 ***
Livestock	-0.000012	0.000016	-0.766182	0.44356809
Flush	-0.017297	0.007795	-2.218917	0.02649237 *

Log-Likelihood: -1,016.2   Adj. Pseudo R2: 0.079037 BIC: 2,224.7   Squared Cor.: 0.127792

6.4.3 High E.coli presence GLMM results

Supplementary Information Table 12: Confusion matrix of results of GLMM of high E.coli contamination with population used as a predictor variable and not latrines.

	Observed class		
Predicted class		No contamination	Contamination
	No contamination	610	56
	Contaminated	105	75

Supplementary Information Table 13: Confusion matrix of results of GLMM of high E.coli contamination with latrines used as a predictor variable and not population.

	Observed class		
Predicted class		No contamination	Contamination
	No contamination	585	53

	Contaminated	131	84

*Supplementary Information Table 14: Results of GLMM of high E.coli contamination with latrines used as predictor variable. Significance codes: *** (0 < p ≤ 0.001); ** (0.001 < p ≤ 0.01); * (0.01 < p ≤ 0.05).*

Variable	Estimate	Std. Error	Z value	p- value
WRU Latrine user density	0.867918	0.779220	1.113829	0.26535
Latrines	0.050621	0.023277	2.179363	0.029305 *
Fertiliser	0.026243	0.024360	1.077293	0.28135
Manure	0.047508	0.028263	1.680932	0.092776
Flood	-0.861073	0.200840	-4.287350	0.000018082 ***
Precipitation	2.946497	1.284146	2.294518	0.021761 *
Cropping intensity	-0.157260	0.327755	-0.479810	0.63136
Anthropogenic biome	-0.000455	0.010695	-0.042514	0.96609
GDRI Poverty	0.010120	0.010163	0.995739	0.31938
Open Defecation	0.006719	0.014333	0.468742	0.63925
Livestock	-0.000093	0.000043	-2.162391	0.030588 *
Flush	-0.031384	0.023084	-1.359594	0.17396

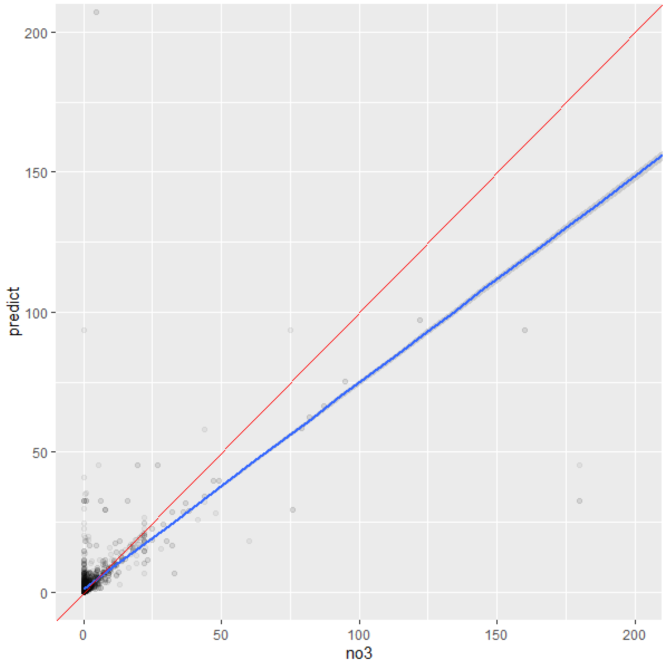
Log-Likelihood: -1,096.5 Adj. Pseudo R2: 0.2404 BIC: 2,400 Squared Cor.: 0.320615

6.4 Random forest model results

6.4.1 Nitrate contamination random forest model

Supplementary Information Table 15: Performance metrics of random forest nitrate contamination model

Model performance metric	Value
Mean Absolute Error (MAE)	1.767276
Mean Squared Error (MSE)	111.0522
Root Mean Squared Error (RMSE)	10.53813
R-squared (R^2)	0.8679921



Supplementary Information Figure 8: Model performance of random forest model. Predicted vs measured nitrate levels are plotted. The trend in predicted vs measured data is shown in blue. The line x=y (perfect performance) is shown in red. Overall, the model underpredicts cases of high measured contamination.

6.4.2 E. coli presence random forest model

Supplementary Information Table 16: Confusion matrix of results of random forest of E.coli presence.

	Observed class		
Predicted class		No contamination	Contamination
	No contamination	387	263
	Contaminated	262	836

Supplementary Information Table 17: Model evaluation metrics for random forest E.coli presence model

Model evaluation metric	Value
Accuracy	0.6997
Precision	0.7614
Sensitivity	0.7607
Specificity	0.5963

6.4.3 High E. coli random forest model

Supplementary Information Table 18: Confusion matrix of results of random forest of high E.coli contamination.

	Observed class		
Predicted class		No contamination	Contamination
	No contamination	1,346 (TN)	222 (FN)
	Contaminated	111 (FP)	69 (TP)

Supplementary Information Table 19: Model evaluation metrics for random forest for high E.coli contamination model

Model evaluation metric	
Accuracy	0.8095
Precision	0.3833
Sensitivity	0.2371
Specificity	0.9238

References

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5.3.1 Postface

This piece of work answered RQ2 by analysing the sources of contamination (taking *E.coli* contamination and nitrate contamination as two contaminants of concern) using a mixed method analysis. By looking at measured contamination from water quality assessments it achieved SO6. Pit-latrine contamination was identified as a major source of both *E. coli* and nitrate contamination, emphasising the significance of sanitation infrastructure on water quality. The work also identified pit-latrine proximity as a better insight than population density to estimate contaminant risk, emphasising the need for better understanding of pit-latrine distribution to manage contamination risks. The identification of pit-latrines as causes of contamination raises even greater concerns when considered within the context of the previous work, underlining the growing risk of high pit-latrine densities to groundwater quality.

5.4 Conclusion to this chapter

This chapter answered RQ2 'What are challenges to groundwater quality in Malawi' by achieving SO4 and developing a novel method to estimate pit-latrine density from population distribution. The chapter evaluates the current extent of boreholes at risk of pit-latrine contamination, estimating that 11.5% of boreholes are currently at risk of contamination due to close pit-latrine proximity. This was validated against data on pit-latrine proximity of a large dataset of water-points (>75,000) which estimated that 15% of boreholes were at risk of pit-latrine contamination. The novel methodology used to estimate pit-latrine risk to water-points was used to achieve SO5 and evaluate future risks of water-point contamination from pit-latrines. The work sheds light on the growing issue of sanitation contamination of groundwater, projecting a three-fold increase in the number of water-points at risk of microbial contamination from 2020-2070 under 'business as usual' projections.

The chapter directly linked pit-latrine density to water quality, achieving SO6, revealing that sanitation-related sources currently pose the greatest threat to groundwater drinking water quality in Malawi. These findings raise serious concerns for domestic water safety and public health, while also presenting a formidable obstacle to achieving SDG6 targets. Additionally, they highlight a significant environmental concern regarding water contamination from sanitation practices. Notably, current sanitation infrastructure poses a greater risk of nitrate contamination of groundwater compared to fertilizer application, emphasizing the urgent need for improved sanitation management strategies to safeguard both human health and environmental integrity.

Critically, this chapter underscored the intrinsic link between sanitation and water, a connection that extends beyond the confines of SDG6. It emphasizes that achieving water security within the framework of SDG6 necessitates comprehensive consideration of both sanitation and water issues. Thus, effective sanitation policy and water policy must be formulated and implemented in tandem, within a complementary framework.

The subsequent chapter delves into the status of sanitation and hygiene in the context of achieving SDG6 objectives in Malawi, address RQ3 and evaluating challenges to sanitation and hygiene provision.

5.4.1 SDG6 targets explored in this chapter

This chapter focused on SDG6.3 ‘water quality and wastewater’, addressing challenges of groundwater contamination. The focus on sanitation infrastructure highlights some challenges in SDG6.2 ‘sanitation and hygiene and end open defecation.’ These are shown in Figure 5.1.

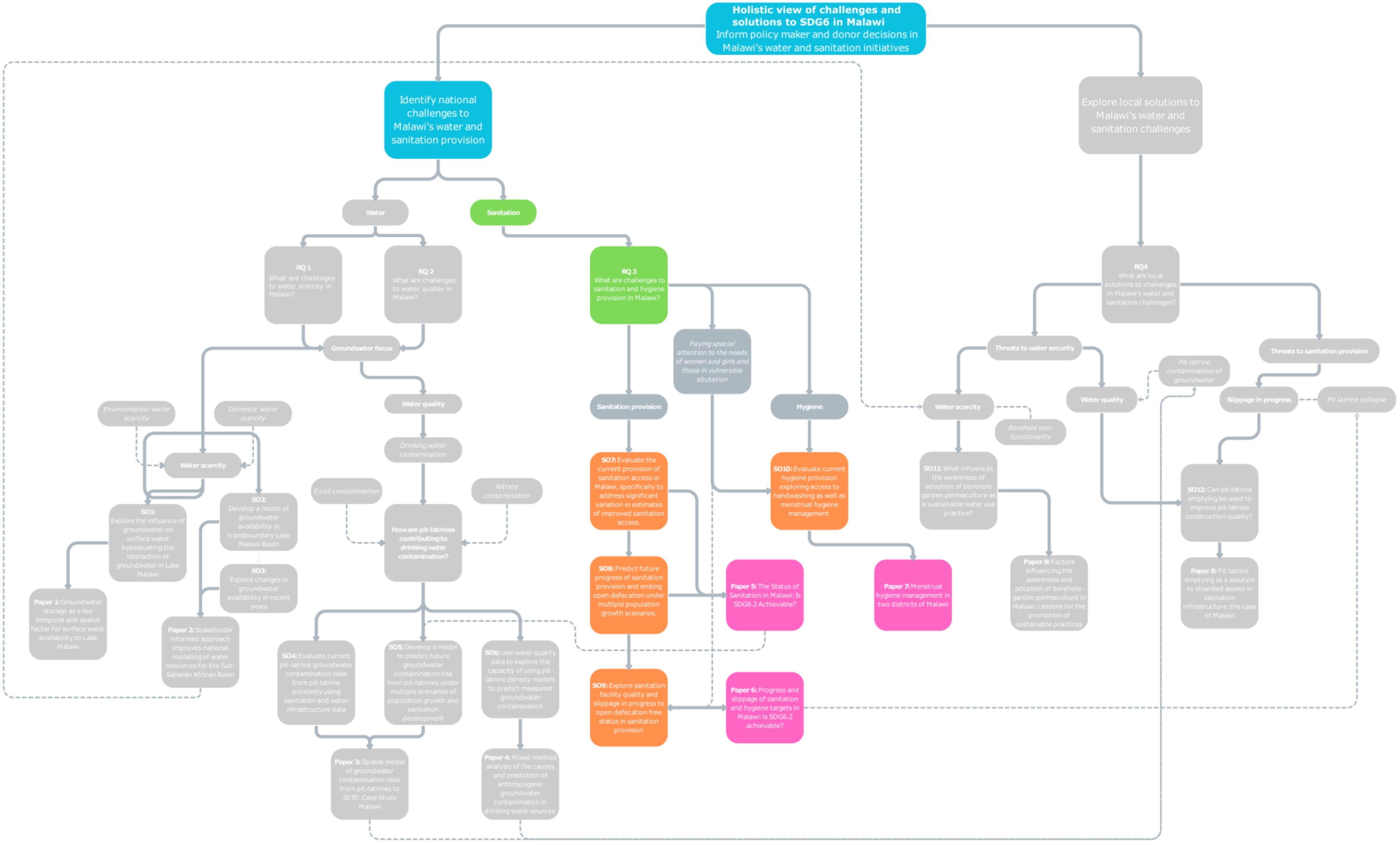
Figure 5.1: SDG6 targets addressed within this chapter. The focus of the chapter is primarly SDG6.3 ‘water quality and waste water’ and SDG6.1 ‘safe drinking water for all’’.

Chapter 6: Challenges to Sanitation and Hygiene Provision for SDG6

"Kuyera kunakanika Chule okhala mmadzi"

(Chichewa expression, Malawi)

"The frog can lack hygiene though he lives in the water"


Holistic view of challenges and solutions to SDG6 in Malawi
Inform policy maker and donor decisions in Malawi's water and sanitation initiatives
Identify national challenges to Malawi's water and sanitation provision
Explore local solutions to Malawi's water and sanitation challenges
Water
Sanitation
RQ 1 What are challenges to water scarcity in Malawi?
RQ 2 What are challenges to water quality in Malawi?
RQ 3 What are challenges to sanitation and hygiene provision in Malawi?
RQ4 What are local solutions to challenges in Malawi's water and sanitation challenges?
Groundwater focus
Environmental water scarcity
Domestic water scarcity
Water scarcity
SO1: Explore the influence of groundwater on surface water byevaluating the interaction of groundwater in Lake Malawi
SO2: Develop a model of groundwater availability in transboundary Lake Malawi Basin
SO3: Explore changes in groundwater availability in recent years
Paper 1: Groundwater storage as a key temporal and spatial factor for surface water availability to Lake Malawi
Paper 2: Stakeholder informed approach improves national modeling of water resources for the Sub-Saharan African Basin
Water quality
Drinking water contamination
E.coli contamination
Nitrate contamination
How are pit-latrines contributing to drinking water contamination?
SO4: Evaluate current pit-latrine groundwater contamination risks from pit-latrine proximity using sanitation and water infrastructure data
SO5: Develop a model to predict future groundwater contamination risk from pit-latrines under multiple scenarios of population growth and sanitation development
SO6: Use water quality data to explore the capacity of using pit-latrine density models to predict measured groundwater contamination
Paper 3: Spatial model of groundwater contamination risks from pit-latrines to 2070: Case Study Malawi
Paper 4: Mixed method analysis of the causes and prediction of anthropogenic groundwater contamination in drinking water sources
Paying special attention to the needs of women and girls and those in vulnerable situtation
Sanitation provision
Hygiene
SO7: Evaluate the current provision of sanitation access in Malawi, specifically to address significant variation in estimates of improved sanitation access.
SO8: Predict future progress of sanitation provision and ending open defecation under multiple population growth scenarios.
SO9: Explore sanitation facility quality and slippage in progress to open defecation free status in sanitation provision
SO10: Evaluate current hygiene provision exploring access to handwashing as well as menstrual hygiene management
Paper 5: The Status of Sanitation in Malawi: Is SDG6.2 Achievable?
Paper 6: Progress and slippage of sanitation and hygiene targets in Malawi: is SDG6.2 achievable?
Paper 7: Menstrual hygiene management in two districts of Malawi
Threats to water security
Threats to sanitation provision
Water scarcity
Borehole non-functionality
Water quality
Pit-latrine contamination of groundwater
Slippage in progress
Pit latrine collapse
SO11: What influences the awareness of adoption of borehole garden permaculture as a sustainable water use practice?
SO12: Can pit-latrine emptying be used to improve pit-latrine construction quality?
Paper 8: Factors influencing the awareness and adoption of borehole-garden permaculture in Malawi: Lessons for the promotion of sustainable practices
Paper 8: Pit latrine emptying as a solution to stranded assets in sanitation infrastructure: the case of Malawi

Chapter 6: Challenges to Sanitation and Hygiene Provision for SDG6

6.1 Introduction

Chapter 5 explored the challenge of ensuring water quality (RQ2) as a crucial aspect in attaining SDG6 objectives in Malawi. It underscored the intrinsic relationship between sanitation infrastructure and water quality, emphasising the necessity of adopting a comprehensive approach to SDG6 and recognising the inherent connection between delivery of 'clean water' and 'sanitation and hygiene'.

In pursuit of a comprehensive understanding of SDG6, this chapter answers RQ3 ‘What are the challenges to sanitation and hygiene provision in Malawi?’. This chapter concentrates on SDG6.2 ‘By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations.’ SDG6.2 constitutes a pivotal objective within SDG6, addressing essential human rights concerning health, dignity, and well-being. Both water quality and the provision of sanitation and hygiene have significant implications for public and environmental health. The importance of reducing the prevalence of waterborne diseases, which pose a substantial health burden in many countries, including Malawi, was underscored in Chapter 5. While Chapter 5 delved into water contamination for waterborne disease management, it is imperative that any management of waterborne disease also integrates considerations for sanitation and hygiene. Without proper sanitation and hygiene measures, improvements in water quality become futile. Sanitation and hygiene provision must also be factored into discussions of environmental sustainability; practices such as open defecation and inadequate sanitation can lead to water source contamination, soil degradation, and pollution, as discussed in Chapter 5. This makes sanitation and hygiene provision, as outlined in SDG6.2, vitally important for public and environmental health.

Yet despite its importance, progress in enhancing sanitation and hygiene provision has been disappointingly slow. On a continental level, substantial leaps are required to achieve SDG6 for Africa with the most significant advancements required in sanitation and hygiene; a 12-fold increase is needed in the current rate of progress to achieve 'safely managed drinking water' for all by 2030 compared to a 20-fold increase for safely managed sanitation and a staggering 42-fold increase for basic hygiene services (WHO and UNICEF 2021). In Malawi, there is a notable lack of clarity regarding the investment and progress required to achieve SDG6.2. This uncertainty is partly attributed to substantial discrepancies in estimates of the proportion of the population meeting sanitation targets; estimates of the population utilizing improved sanitation range from 6% to over 80% (US Aid, 2022; NSO and Macro International, 2016) The absence of a consensus on the status of sanitation within Malawi hampers effective policy making and appropriate monitoring of progress toward SDG6. A more comprehensive understanding of both current and future sanitation challenges is imperative, not only to attain SDG6.2 but also to address other targets within SDG6.

Another critical aspect of SDG6.2 revolves around meeting the needs of women and girls who often face a disproportionate burden from inadequate sanitation facilities, particularly relating to privacy concerns, safety risks, and limited access to menstrual hygiene management resources in accessing sanitation and hygiene. By recognising the unique challenges faced by women, girls, and marginalized communities, SDG6.2 addresses gender equality considerations within the broader framework of SDG6. However, this aspect is frequently overlooked in research, with little information available on the challenges related to security, privacy, and menstrual hygiene management within national assessments of sanitation and hygiene provision in Malawi. There is a need not only to enhance monitoring and comprehension of sanitation provision but also to place a central focus on understanding the requirements of women and girls within this.

This chapter provides a comprehensive exploration of SDG6 by delving into sanitation and hygiene provision, highlighting significant policy implications for SDG6.2 in Malawi. In particular, the chapter addresses RQ3 through responding to the specific objectives:

SO7: Evaluate the current provision of sanitation access in Malawi, specifically to address significant variation in estimates of improved sanitation access.

SO8: Predict future progress of sanitation provision and ending open defecation under multiple population growth scenarios.

SO9: Explore the sustainability of progress to open defecation elimination

SO10: Evaluate current hygiene provision exploring access to handwashing as well as menstrual hygiene management.

This chapter is composed of a series of papers published or submitted to international peer-reviewed journals detailed below:

Paper 5

Hinton, R. G. K., Macleod, C. J. A., Troldborg, M., Kanjaye, M. B. & Kalin, R. M. (2023). The Status of Sanitation in Malawi: Is SDG6.2 Achievable? *Int J Environ Res Public Health 20.*

Author contribution:

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

Paper 6

Hinton, R.G.K., Tremblay-Lévesque, L.C., Macleod, C. J. A., Troldborg, M., Kanjaye, M., Kalin, R.M. (*In Review*). Progress and slippage of sanitation and hygiene targets in Malawi: is SDG6.2 achievable? *Journal of Water, Sanitation and Hygiene for Development.*

Author contribution:

Conceptualization (R.G.K.H, R.M.K, M.K., L.C.T.L) data curation (L.C.T.L R.M.K), formal analysis (R.G.K.H), investigation (R.G.K.H), methodology (R.G.K.H., L.C.T.L., C.J.A.M., M.T., R.M.K.), validation (L.C.T.L, R.G.K.H.), visualization (R.G.K.H), project administration (R.M.K), supervision (R.M.K, C.J.A.M, M.T), writing original draft (R.G.K.H), review and editing (R.G.K.H, L.C.T.L., R.M.K., C. J.A.M, M. T, M. K,)

Paper 7

Hinton, R.G.K., Tremblay-Lévesque, L.C., Macleod, C. J. A., Troldborg, M., Kanjaye, M., Kalin, R.M. (*In Review*). Menstrual hygiene management in two districts of Malawi. *PLOS Global Public Health.*

Author contribution:

Conceptualization (R.G.K.H, R.M.K,. L.C.T.L) data curation (L.C.T.L R.M.K), formal analysis (R.G.K.H), investigation (R.G.K.H), methodology (R.G.K.H., L.C.T.L., C.J.A.M., M.T., R.M.K.), validation (L.C.T.L, R.G.K.H.), visualization (R.G.K.H), project administration (R.M.K), supervision (R.M.K, C.J.A.M, M.T), writing original draft (R.G.K.H), review and editing (R.G.K.H, L.C.T.L., R.M.K., C. J.A.M, M. T, M. K,)

6.2 The Status of Sanitation in Malawi: Is SDG6.2 Achievable?

Article

Rebekah G. K. Hinton [1,2,*], Christopher J. A. Macleod [2], Mads Troldborg [2], Modesta B. Kanjaye [3] and Robert M. Kalin [1]

[1] Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, G1 1XJ, UK;
robert.kalin@strath.ac.uk
[2] The James Hutton Institute, Craigiebuckler, Aberdeen AB15 8QH, UK;
kit.macleod@hutton.ac.uk (C.J.A.M.); mads.troldborg@hutton.ac.uk (M.T.)
[3] Ministry of Water and Sanitation, Government of Malawi, Private Bag 390, Lilongwe, Malawi; modesta.banda@gmail.com

*Correspondence: rebekah.hinton@strath.ac.uk

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Abstract: Ensuring access to adequate and equitable sanitation and ending open defecation by 2030 is the focus of Sustainable Development Goal 6.2 (SDG6.2). We evaluated Malawi's progress towards SDG6.2 (specifically the goal to end open defecation), presenting the results of a national survey of over 200,000 sanitary facilities and evaluating their management. Based on non-linear population dynaMICS, we used a linear model to evaluate the reduction in open defecation between 1992–2018, and to project whether Malawi can meet the SDG target to end open defecation by 2030 under multiple scenarios of population growth. Whilst Malawi has made considerable progress in providing sanitary provision for the population, we estimate that, at the current rate of the provision of sanitary facilities, Malawi will not reach SDG6.2 by 2030 under any of the modelled socioeconomic scenarios. Furthermore, we compare the estimates of the extent of sanitary provision classed as improved from multiple surveys, including the USAID Demographic and Health (DHS) Surveys and Government of Malawi Census data. We conclude that some of the surveys (particularly the 2015/16 DHS) may be overestimating the level of improved sanitary provision, and we hypothesize that this is due to how pit-latrines with earth/sand slabs are classed. Furthermore, we examine the long-term sustainability of pit-latrine use, investigating the challenge of pit-latrine abandonment and identifying pit-latrine filling as a cause of the abandonment in 30.2% of cases. We estimate that between 2020–2070, 31.8 (range 2.8 to 3320) million pit-latrines will be filled and abandoned, representing a major challenge for the safe management of abandoned latrines, a potential for long-term impacts on the groundwater quality, and a significant loss of investment in sanitary infrastructure. For Malawi to reach SDG6.2, improvements are needed in both the quantity and quality of its sanitary facilities.

Keywords: sustainable development goals; sanitation; open defecation; Malawi; linear model; survey

1. Introduction

Safe and accessible sanitation has been declared a fundamental human right [1]. Sanitation is central to human health, not only through disease prevention but also the promotion of human dignity and well-being [2]. A lack of safe water and sanitation is the world's largest cause of illnesses [3]; many of these illnesses are caused by diarrheal disease, which remains the second leading cause of death in children under five, killing 525,000 children under five each year [4]. In addition to the health benefits, improvements in sanitation systems have, in some cases, been shown to have net economic benefits through a reduction in adverse health effects and health-care costs [5]. Significant steps have been made in improving access to sanitation, with over 2.1 billion people gaining access to at least basic sanitation services between 2000–2017 [6]. A lack of safe sanitation puts users at risk of faecal-oral diseases, including through exposure to contaminated drinking water. An estimated 1.8 billion people regularly use water contaminated with faeces, with 1.1 billion drinking water supplies that have an at-least moderate risk of faecal contamination [7]. Faecal contamination of water can be a source of pathogenic bacteria, viruses, protozoa, and helminths [5].

Consequently, safe sanitation is foundational to meeting several of the Sustainable Development Goals (SDGs) [2]. Globally, progress in sanitation improvements has been slow [8], with over 3.6 billion people (46% of the global population) still lacking access to safely managed sanitation and it is estimated that at the current rate of progress, 33% of the global population will still be left without safely managed sanitation by 2030 [8]. Furthermore, the number of people lacking access to improved sanitation services is only expected to grow [3]. SDG6 target 2 outlines the goal of achieving access to “adequate and equitable sanitation and hygiene for all and end open defecation by 2030” [9], with indicator SDG6.2.1.a reporting on the “proportion of the population using safely managed sanitation services” specifically [10]. Many sources report different metrics of sanitary access, including the proportion of the population with safely managed sanitation, adequate sanitation, basic sanitation, and improved sanitation [3,8,9]; this can make drawing comparisons challenging. Improved sanitation services are widely defined as ‘sanitary systems that minimize human contact with excreta including flush/pour latrines, ventilated improved pit (VIP) latrines, pit-latrines with a slab, and composting toilets’ [11], and will be defined as such for the purposes of this work. The proportion of the population with basic sanitation is defined as the percentage of the population with ‘improved sanitation facilities that are not shared with other households’ [12]. Safely managed sanitation facilities go a step further and are defined as the ‘population using an improved sanitation facility that is not shared with other households and where excreta are safely disposed of in situ or treated off site’ [13,14].

Among those lacking basic sanitation, over half live in sub-Saharan Africa [8]. Like much of sub-Saharan Africa, Malawi has a high proportion of the population without access to improved or basic sanitation. There is large variation in the estimated levels of access to sanitation in Malawi, where the percentage of the population using improved sanitation ranges between 6% [15] and 88% [16]. The 2015/16 DHS estimated that 52% of households used an improved facility [17], whilst the government’s policy document Malawi 2063 [14] estimates that 35.2% of households were using safely managed sanitation services in 2020. Malawi’s 2008 National Sanitation Policy estimated that access to improved sanitation was low, estimated as between 25–33% and dropping to less than 7% in some rural communities [18]. Malawi’s 2008 National Sanitation Policy aimed to ensure 100% of the population had access to improved sanitation by 2020;

however, this target has not been met [18]. A new goal was set out in Malawi's 2063 policy document that similarly aimed to expand sanitation services to 100% of households, but specifying a 100% use of safely managed sanitation services with a 2060 target [14]. To ensure that Malawi can meet its target [14], a revision of the 2008 National Sanitation Policy (Malawi) is needed. This revision should be informed by the status of sanitation provision, and focus on the required changes to achieve 100% coverage.

There is further consensus on the level of open defecation in Malawi. In 2018, the Malawi Census estimated that 5.9% of the population were practicing open defecation [19], the World Bank and UNICEF also estimated that 6% of the population were practicing open defecation in 2018 [20,21]. Malawi's government, working with NGO's, has successfully reduced the extent of open defecation, with the percentage of the population without access to sanitary facilities falling from 27.7% [22] in 1992 to 5.9% in 2018 [19].

Population growth may undermine Malawi's efforts to eliminate open defecation if the rate of population growth outpaces the provision of sanitary facilities; Malawi's population is projected to increase five-fold in this century [23]. To model this non-linear growth, we chose the five Shared Socioeconomic Pathways (SSP) [24], which are outline scenarios of population growth and urbanization considering age, sex, and education [25]. Modelling the trends in sanitary provision under the current rate of growth of sanitary access and different scenarios of population growth enables projections to be made for open defecation under different socioeconomic scenarios. Projecting the level of open defecation enables an estimation of whether Malawi will meet the most basic requirement of SDG 6: ensuring access to sanitation.

To meet SDG 6—ensuring access to "safely managed" sanitation [9]—the type and management of sanitary facilities must be considered. This study explored not only the level of access to sanitary facilities, but also the type and management of the sanitary facilities. The extent of the access to improved sanitation was evaluated by investigating the type of sanitation facility through comparing the Government of Malawi Census results [19], US Aid DHS results [17,26], and the results of our extensive sanitation survey presented here. Furthermore, the survey explores the nature of sanitary management, including the disposal of non-human waste in latrines and the level of latrine collapse.

This paper evaluates Malawi's progress in striving to reach SDG6.2 through evaluating the access to adequate and 'improved' sanitation services, as well as the extent of open defecation. Using an extensive, country-wide, sanitation survey, we explore the types of sanitary facilities being used and the nature of sanitary management in Malawi to address the following research questions: (1) How do our estimates of sanitary provision compare with stakeholder estimations, including the Government of Malawi, USAID, and UNICEF; (2) How are sanitary facilities managed and what are the major challenges in the management of sanitary facilities, including the disposal of non-human waste in latrines and the level of latrine collapse; (3) When, if it all, can Malawi reach open defecation-free status at the current rate of sanitary facility provision under a range of socioeconomic scenarios of population growth? These analyses provide a holistic view of whether Malawi is on track to provide safe and accessible sanitation before 2030 and whether SDG6.2 is an achievable 2030 goal.

2. Materials and Methods

2.1. Study Area

Much progress has been made in providing sanitation in Malawi, with a reduction in the percentage of the population practising open defecation, from 27.7% in 1992 [22] to 5.9% in 2018 [19]. This has involved not only the provision of sanitary facilities to the population that previously had no sanitary provision, but also providing sanitary provision for a growing population. The population of Malawi is currently almost 20 million [27] and is rapidly increasing, with an annual growth rate of 2.7% [28]. Under 'business as usual' population growth, modelled by the Shared Socioeconomic Pathway (SSP) Scenario 2 (SSP2), Malawi's population is projected to reach 26.3 million by 2030 and 53.6 million by 2070 [24,25]. However, in the high population growth scenario, SSP3 projects that Malawi's population could reach 72.1 million by 2070 [24,25]. The population growth puts increasing pressure on

Malawi's sanitation systems. Increasing urbanization also concentrates sanitary requirements, placing pressure on urban systems [14].

Providing sufficient, consistent, long-term investment into sanitation infrastructure is a challenge. Malawi is one of the least developed countries globally, classed as low, with a Human Development Index (HDI) of 0.483 in 2019, which is below the 0.513 threshold [29]; this is despite improvements in the HDI from 0.333 in 1990. Malawi is furthermore below the Sub-Saharan African average HDI value of 0.547 [29]. In addition, Malawi's economy is particularly vulnerable to climatic shocks due to its reliance on agriculture, accounting for almost one-third of the GDP of Malawi [30], and employing over 80% of the population [31]. These factors limit a resource base for long-term investment into sanitary (and water) infrastructure.

2.2. Data

Data on the percentage of the population using different types of sanitary facilities were gathered from open-source reports, including the USAID Demographic Health Surveys (DHS) [17,22,26,32,33], Government of Malawi Census Data [19], and USAID Malaria Indicator Surveys (MIS) [34,35]. Data were also sourced from the UNICEF Child-related SDG Indicators [36], USAID estimates [16], and Government of Malawi estimates [14]. The number of households surveyed in the DHS, MIS, and Census is summarized in Table 1. The number of households was not provided for the UNICEF, USAID, and Government of Malawi estimates.

A survey conducted by the Government of Malawi through the Scottish Gov't Climate Justice Fund Water Futures Programme (CJF) of 268,180 sanitation facilities was used to indicate the nature of the sanitary facilities in Malawi (Figure 1) [37–40]. The surveys were conducted by trained Government of Malawi surveyors in Chichewa and English. The responses were quality controlled by the University of Strathclyde. The data were hosted on the online platform mWater [41]. Questions were asked regarding the type of sanitary facility, usage, and the management of the sanitary facility. The types of sanitary facilities classified in each survey are summarized in Table 1. Questions were also asked about previous facilities if the facility was a replacement to a previously filled/abandoned facility. The data were cleaned to remove duplicate responses (some sites were visited more than once over time), incomplete answers, and to restrict responses to 2018–2019, resulting in 201,782 complete responses (75.2%).

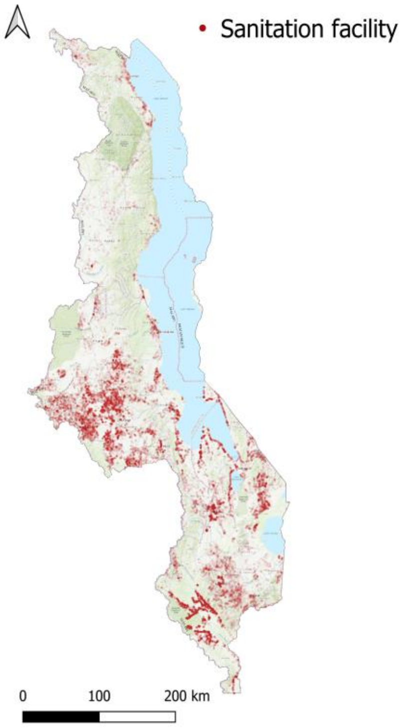

Figure 1. Location and distribution of the 268,180 sanitation surveys undertaken nationally across Malawi for the CJF programme. Map produced in QGIS [42]. Map background World Topo Map basemap [43].

Table 1. Summary of DHS, Census, and CJF Surveys, including the number of households/sanitary facilities surveyed and the classifications of sanitation facilities in the survey. Sanitary facilities that were classed as improved for the purposes of this study are marked with an asterisk (*).

Source	Year	Number of Households/Sanitation Facilities Surveyed	Types of Sanitation Facilities Classified
DHS	2010	24,825	Flush/pour flush to piped sewer system *; Ventilated improved pit (VIP) latrine *; Pit-latrine with slab *; Any facility shared with other households; Pit-latrine without slab/open pit; No facility/bush/field; Other; Missing
DHS	2015/16	24,721	Flush/pour flush to: piped sewer system *, septic tank *, pit-latrine *; Ventilated improved pit (VIP) latrine *; Pit-latrine with slab *; Composting toilet *; Shared facilities (that would be considered improved if they were not shared by two or more households); Pit-latrine without slab/open pit; Bucket; No facility/bush/field
Census	2018	3,984,981	Flush toilet *; Ventilated improved pit (VIP) latrine *; Pit-latrine with concrete slab *; Pit-latrine with earth/sand slab *; Composite toilet *; Pit-latrine without slab/open pit; No facility/bush/field;
CJF survey	2018/19	201,782	Flush/Pour flush toilet *; Ventilated improved pit (VIP) latrine *; Pit-latrine with slab *; Composting

	toilet *; Hanging toilet; Hanging latrine; Pit-latrine without slab/open pit; Bucket; Other;

2.3. Status of Access to Adequate Sanitation in 2018/19

An estimate of the percentage of the population with access to adequate sanitation between 2015 and 2020 was taken from a number of sources. In cases where the source listed the percentage of the population using improved sanitation, this was used as the estimate. In cases where the percentage of the population using improved sanitation was not listed, the percentage of the population using each type of sanitary facility classed as improved [11] was summed. In cases where the type of sanitary provision was divided between shared or individual sanitary facilities [22], the total number of people using each type of sanitary facility (shared and personal facilities) was summed.

The CJF Survey only investigated established sanitary facilities; therefore, the percentage of the population using each sanitary type within the DHS [17,26] and Census [15] had to be scaled to the percentage of the population with sanitary access, using each sanitary facility type (as per the specification of the SDG6.2 indicator) within the CJF Survey. Therefore, the percentage of the population using each type of sanitary facility was divided by the total percentage of the population using any of the types of sanitary facilities listed within the CJF Survey.

To estimate the percentage of the population with no access to improved sanitation, the results of the CJF Survey were scaled to account for the percentage of the population practicing open defecation. The percentage of the population using each type of sanitary facility was multiplied by the percentage of the population with access to sanitary facilities (from the 2018 Census data) [19].

To further evaluate the management of sanitary facilities, questions regarding latrine management were asked. Participants were asked what waste, other than faecal waste, was deposited in the sanitation facility. Questions were also asked about previously abandoned latrines, including why they were abandoned, how quickly it took for the previous latrine to fill up, and what was done to decommission the previous latrine. Answers were given through multiple choice.

2.4. Trends in Access to Sanitation

Evaluating the proportion of the population practicing open defecation provides a method to investigate the level of access to some sanitation provision in Malawi, thereby giving an indication of whether the country is on track to achieve the Sustainable Development Goals (SDGs).

All individuals not practicing open defecation were assumed to have access to a sanitary facility (improved or non-improved). The number of individuals with access to sanitary facilities per year was calculated from the product of the population for a given year and the percentage of the population not practicing open defecation. The number of individuals gaining access to sanitation provision each year was calculated from the change in the number of individuals with access to sanitary facilities. This includes people who were previously practicing open defecation and had received sanitation provision in a given year, as well as any increases in the population that have access to sanitary facilities. The rate of change in the number of people practising open defecation was calculated using Equation (1):

$$\frac{\boldsymbol{d(P\ OD)}}{\boldsymbol{dt}} = \frac{(\boldsymbol{P}_{(\boldsymbol{year+t})}\boldsymbol{OD}_{(\boldsymbol{year+t})})-(\boldsymbol{P}_{\boldsymbol{year}}\boldsymbol{OD}_{\boldsymbol{year}})}{\boldsymbol{t}} \tag{1}$$

The percentage of the population practising open defecation for a given year was calculated using Equation (2):

$$\boldsymbol{OD}_{(\boldsymbol{year+t})} = \frac{(\boldsymbol{t}\frac{\boldsymbol{d\ (P\ OD)}}{\boldsymbol{dt}}+\boldsymbol{P}_{\boldsymbol{year}}\boldsymbol{OD}_{\boldsymbol{year}})}{\boldsymbol{P}_{(\boldsymbol{year+t})}} \tag{2}$$

where $\boldsymbol{P}$ is the population size (in millions), $\boldsymbol{t}$ is the time-window being considered (in years), year is the year, and $\boldsymbol{OD}$ is the percentage of the population practicing open defecation.

Due to the uncertainty bounds and variation between the datasets, the trend in sanitary facility provision between 1992–2018 was calculated using a simple linear regression model, using the linear model (lm) function under the stats package in base R [44], thereby projecting a conservative estimate of the number of people with access to sanitary facilities. The estimated trend in sanitary provision is assumed to be constant. Estimates of the percentage of the population without access to basic sanitation were generated by subtracting the projected number of people with sanitary provision from the projected population of Malawi each year under multiple socioeconomic scenarios of non-linear population growth. Alternative scenarios of population growth were modelled using the 5 Shared Socioeconomic Pathway (SSP) population growth scenarios [24,25]. These outline 5 global scenarios of socioeconomic changes and provide a range of scenarios of population growth in Malawi.

The SSP scenarios under which Malawi achieved Sustainable Development Goal 6.2, to end open defecation by 2030 [9], were evaluated. Scenarios in which Malawi reaches its own development plan target of 100% of households using safely managed sanitation by 2060 [14] were also determined.

2.5. Projecting the Number of Abandoned Pit-Latrines

The cumulative number of abandoned pit-latrines due to filling projected over a given period was calculated using Equation (3):

$$\boldsymbol{A = \frac{P_l}{U\,F}\int_{t=year}^{year+T} PT_t\,dt} \tag{3}$$

where $\boldsymbol{A}$ is the cumulative number of abandoned pit-latrines, $\boldsymbol{P_l}$ is the fraction of the population with toilet access using pit-latrines, $\boldsymbol{U}$ is the number of users that share a pit-latrine, $\boldsymbol{F}$ is the time (in years) taken for a pit-latrine to fill up, year is the calendar year of the first year considered in the time span investigated, $\boldsymbol{T}$ is the length of time (in years) being considered, and $\boldsymbol{PT}$ is the population (million) with access to sanitary facilities.

The fraction of the population with access to a toilet ($\boldsymbol{PT}$) using pit-latrines ($\boldsymbol{P_l}$) is estimated from the CJF Survey. The equation assumes that the percentage of people using pit-latrines does not change over time (assumed to be a valid assumption given the current lack of a fiscal resource base for enhanced sanitation investment). The population with toilet access (millions)

(***PT***) is then calculated from a linear trend in sanitary provision, forecasting the number of people gaining sanitary access each year.

The number of users sharing a pit-latrine (***U***) and the time taken for a latrine to fill (***F***) are estimated from the results of the CJF Survey. An upper bound and lower bound estimation are approximated, and a weighted average is calculated. We estimated the weighted average of users and time taken to fill a pit-latrine by multiplying the median value in each range of users/ time taken to fill the latrine by the proportion of responses in this range and summing all the values. For the upper range of 'more than 20 users', we estimated an upper limit of 30 users (therefore an average of 25.5 users); the Sphere project recommends that one latrine should have no more than 20 users [45]. For the upper limit of the time-taken to fill the pit-latrine within the 'more than 3 years' response, we used an upper estimate of 20 years, based on the literature [46,47], resulting in an average of 11.5 years for the upper range.

3. Results

3.1. Results of the Access to Adequate Sanitation in 2018/19

Some facilities were measured through time; therefore, only the most recent survey was chosen for analysis, leaving 201,782 unique sanitary facility surveys selected for analysis from the CJF Survey. The sanitary facilities were grouped into the type of facility. The breakdown of the total numbers of each facility type is summarized in Figure 2 and Table 2; 24.2%, 69.3%, 88.5%, and 10.4% of sanitary facilities were classed as improved in the 2018/19 CJF Survey, 2018 Census [19], 2015 DHS [17], and 2010 DHS [26], respectively.

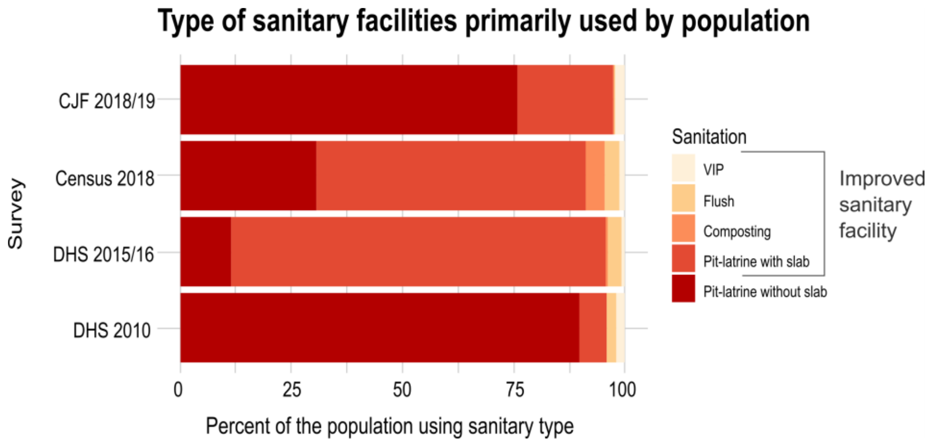

Figure 2. Results are grouped into 5 types of sanitary facility. The percentage of the population using each facility type includes facilities that are both shared and individual to enable comparison between surveys. Based on the type of sanitary facilities only, not accounting for whether they are shared, improved facilities are Ventilated Improved Pit-latrines, Flush latrines (including to sewer system, septic tanks, and pit-latrines), compositing toilet, and pit-latrines with slabs. Pit-latrines without slabs are classified as a non-improved facility.

Table 2. Italics are used where the percentage of the population referred to includes shared facilities. An asterisk (*) marks cases where the percentage of the population includes cases where sanitary facilities are classed as 'other' or missing values. Bold indicates figures where the result has been calculated by scaling estimates between the percentage of the population and the percentage of sanitary facilities.

Source	Year	Population Using Improved Sanitation (%)	Population Practising OD (%)	Households Using Improved Sanitation (%)	Sanitary Facilities Classed as Improved (%)
US Aid	2022	6			
UNICEF	2020	24.2	6.0		**25.7**
DHS	2010	8.8	9.9 (* *15.4*)	8.2	**10.4**
DHS	2015/16	55.1 (*83.7*)	5.4	51.8 (*83.0*)	**88.5**
Census	2018	63.8	5.9 (* 7.8)	62.3	**69.3**
GOM Malawi 2063	2020			35.2	
CJF survey	2018/19	**23.0**			24.2

The CJF Survey found that most of the surveyed sanitation facilities were unimproved facilities, with 75.6% of the surveyed latrines being classed as 'pit-latrines without a slab'. The only survey that broke down pit-latrines by the type of slab was the 2018 Census [19], which found that 83.2% of non-VIP (Ventilated, improved pit-latrine) pit-latrines with slabs had earth/sand slabs (used by 46.3% of the population), whilst 16.8% had concrete slabs (used by 9.4% of the population). This study classed all pit-latrines with a slab as improved, as was the case in the 2010 and 2015/16 DHS [18,26]. If the pit-latrines with an earth/sand slab were not classed as improved sanitary facilities, the percentage of sanitary facilities in the 2018 Census that would be classed as improved would be 19.0%.

The usage of pit-latrines was further evaluated to identify the challenges in pit-latrine management. In response to the question "Other than human waste what materials are disposed of in this sanitation facility", 11.7% of sanitary facilities had nothing other than human waste deposited in the pit-latrine. Ashes were the most common non-human waste deposited in the pit-latrine, with 77.1% of pit-latrines having ashes deposited in them. Oil was deposited in 8.32% of pit-latrines, rubbish (including plastic bags) was deposited in 6.98% of cases, and mulching materials were deposited in 2.66% of cases.

The reasons for which a latrine was abandoned were also examined. The most common reasons latrines were abandoned were collapse from rainfall (55.7%), filling up (30.2%), and replacement by a new facility (10.7%). Other reasons included abandonment due to proximity to a water-point (1.0%), lack of money to pay a pit-emptier/ builder (1.4%), and lack of technical knowledge to build a new latrine (0.9%). Further investigation is needed to establish why the latter point would be a reason for the abandonment of a pit-latrine.

In cases where the latrine was a replacement for a previous latrine that had filled up, the participants were asked about the amount of time the previous latrine took to fill. A total of 111,377 latrines were replacements for previously filled latrines. Figure 3 and Table 3 show how long it took for these latrines to fill up, as well as the number of users. Most latrines took over 3 years to fill up (59.2%), 22.6% of latrines filled up in 2–3 years, 14.7% filled in 1–2 years, 3.0% filled in 6 months to 1 year, and 0.5% filled in less than 6 months. Overall, the survey attained responses regarding how many people used 88,395 of the previously filled latrines.

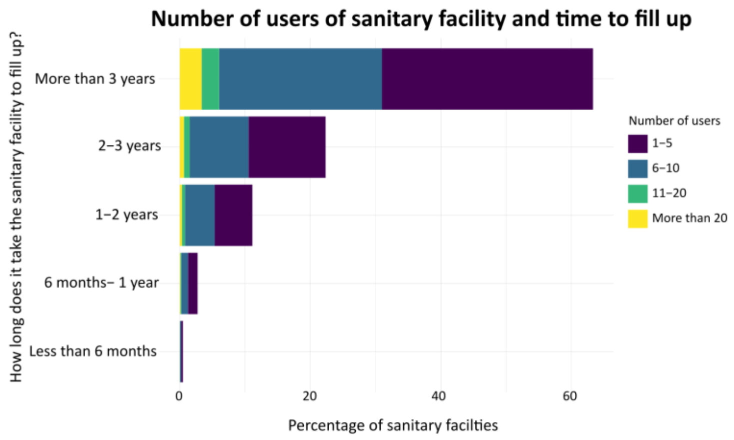

Figure 3. The number of people who use the sanitary facility and how long it took the previous sanitary facility (for which the current facility is a replacement) to fill up.

Table 3. Number of users using the latrine and the time it takes a pit-latrine to fill up. On average, 51.7% of pit-latrines had 1–5 users, 39.7% had 6–10 users, 4.2% had 11–20 users, and 4.4% had more than 20 users. The distribution of the number of latrine users within each group of filling up rate was not statistically significantly different from the overall percentage of the number of latrine users for all latrine filling rates. The data values and ANOVA results are summarized in the appendix, table A1 . u

Time to Fill Up	**1–5 Users (%)**	**6–10 Users (%)**	**11–20 Users (%)**	**More Than 20 Users (%)**
More than 3 years	51.1	39.4	4.2	5.3
2–3 years	52.9	40.3	3.95	2.85
1–2 years	51.9	40.9	4.33	2.84
6 months–1 year	54.2	37.4	5.22	3.15
Under 6 months	56.3	36.6	4.02	3.07

Alongside recording how long they took to fill up, 9478 surveyed sanitary facilities had responses explaining how the previous latrine was decommissioned. Overall, 58.4% of these latrines were decommissioned without any kind of decommissioning process, 34.3% were covered over, and 6.5% were filled in. In addition, 0.9% of the abandoned latrines were emptied or the waste was used for other purposes, 0.7% were mulched over and used for fertilizer, and 0.2% of latrines were emptied.

3.2. Trends in Access to Sanitation

To evaluate Malawi's progress in providing sanitary provision for the population and to end open defecation, the trend in the population gaining access to sanitary facilities was evaluated. The open-source data were obtained from the US Aid Demographic Health Surveys (DHS) [17,22,26,32,33], Government of Malawi Census Data [18], and US Aid Malaria Indicator Surveys (MIS) [34,35]. Table 4 summarizes the number of people who had access to sanitary facilities as recorded in the DHS, MIS, and Census data between 1992 and 2018. The mean number of people who gained access to sanitary facilities each year is also given.

Table 4. Change in the population of Malawi and the number of people with access to sanitary facilities from US Aid Demographic Health Surveys (DHS) [17,22,26,32,33], Government of Malawi Census Data [19], and US Aid Malaria Indicator Surveys (MIS) [34,35] from 1992 to 2018.

Source	**Year**	**Population/ Million**	**Number of Households Surveyed**	**Percentage of The Population Practising Open Defecation**	**Number of People Practising Open Defecation/Million**	**Mean Annual Increase in Sanitation Access/Million**
DHS	1992	9.69	5323	27.7	2.68	0.261
DHS	2000	11.2	14,213	18.5	2.06	0.308
DHS	2004	12.3	15,041	16.1	1.98	0.442
DHS	2010	14.5	24,825	10.8	1.57	0.114
MIS	2012	15.4	3500	14.3	2.20	0.552
MIS	2014	16.3	3501	12.2	1.99	0.704
DHS	2015/16	16.8	24,721	6.2	1.04	0.386
Census	2018	17.5	3,984,981	5.9	1.03	

Figure 4 shows the estimated trend in the number of people given access to sanitary facilities; the confidence intervals and residuals for the trend are given in Appendix B. The historic trend is projected forward to forecast the rate at which sanitary access will be provided.

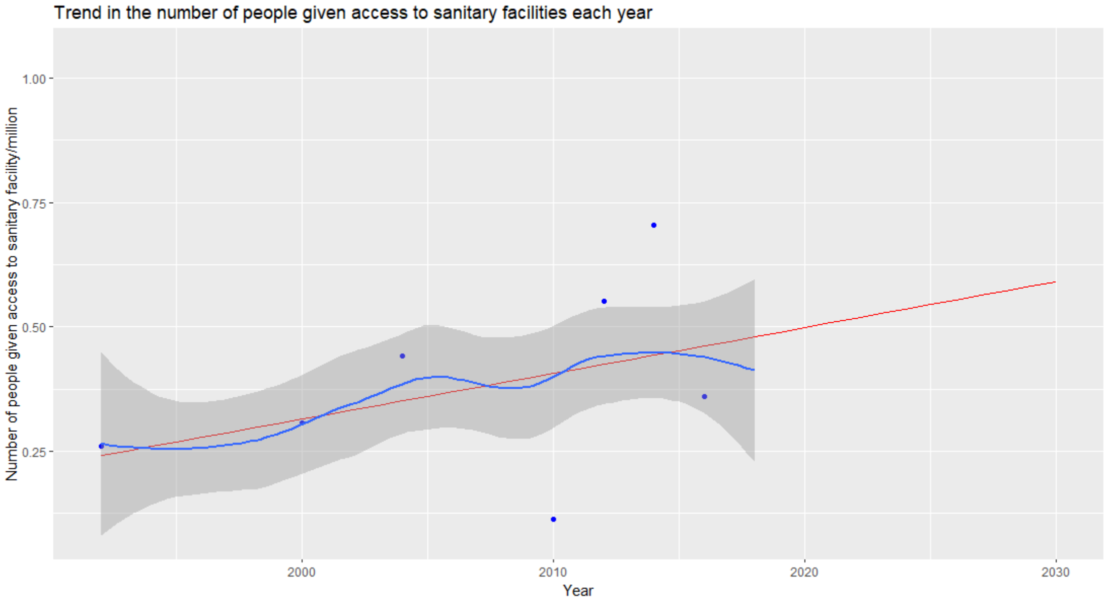

Figure 4. Trend in the number of people given access to sanitary facilities each year. The historical trend (data summarized in Table 4) is shown in blue. The forecast trend, through generating a linear model from the historical data, is shown in red.

The data in Figure 5 summarize the projected percentage of the population with access to sanitary facilities until 2070 under multiple scenarios of population growth. No SSP scenarios [24,25] project that Malawi will reach 100% access to sanitary facilities (an end to open defecation) by 2030—a necessity to meet SDG 6—under the current rate of sanitary facility access and a key part of the Malawi 2063 plan [14]. Under SSP1 and SSP5, Malawi is projected to achieve an end to open defecation before 2035; SSP2 estimates that this will be reached by 2060. However, scenarios SSP3 and SSP4 project that there would be an increase in open defecation as the rate of population growth would outpace the rate of the increase in sanitation access. The uncertainty in the linear model is shown in Figure A1 Appendix B.

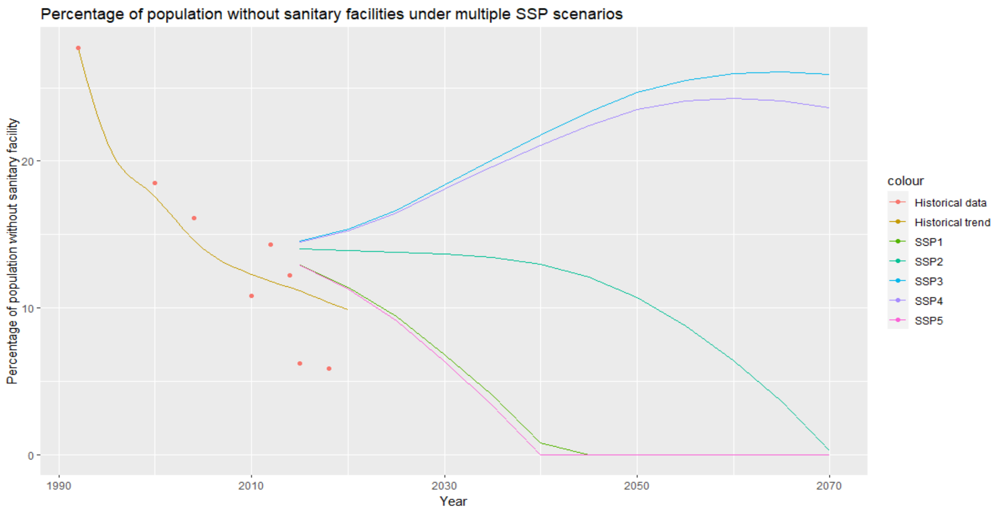

Figure 5. The percentage of the population without access to sanitary facilities (assumed to be practicing open defecation) under multiple socioeconomic scenarios of non-linear population growth. The historic trend (based on DHS [17,22,26,32,33], Census [19], and MIS data [34,35]) is shown alongside historical data points (from individual reports) and the projected open defecation estimates based on population growth scenarios for SSPs 1–5 [24,25].

3.3. Projecting the Number of Abandoned Pit-Latrines

The number of abandoned pit-latrines projected between 2020–2070 was calculated using Equation (3). The percentage of the population with toilet access using pit-latrines was calculated from the CJF 2019 Survey, summing the percentage of the population using pit-latrines (with slab, without a slab, and VIP latrines). The percentage of the population with sanitary access utilising pit-latrines (Pl) was estimated as 99.4%.

The number of users ranged from “1–5 users” to “More than 20 users”, whilst the average time taken to fill the pit-latrine ranged from “Less than 6 months” to “More than 3 years”. For the purposes of this study, we estimate a lower bound number of users as 1 and an upper bound of 30 users; we estimate a lower bound of 6 months filling time for a pit-latrine and an upper bound of 20 years.

We estimate weighted averages of 8.03 years before the latrine filled and 6.50 users. The weighted averages are shown in Appendix C.

Between 2020–2070, there were a projected 1670 million annual toilet users in Malawi (assuming a continuous trend in the number of people with access to toilets) and 1660 million annual pit-latrine users. Taking the weighted averages for the pit-latrine fill up time and number of users, we estimate that there would be *31.8 million pit-latrines abandoned due to filling up between 2020–2070*. The calculated number of abandoned pit-latrines ranged from an upper estimate of 3320 million pit-latrines (assuming one latrine per user and the pit-latrine fills up every 6 months) to a lower bound of 2.77 million pit-latrines (assuming each pit-latrine is shared by 30 users and fills every 20 years).

4. Discussion

The CJF Survey results estimated that 23.0% of Malawi's population used improved sanitary facilities (24.4% of the 201,782 sanitary facilities were categorized as improved); this was close to the 2020 UNICEF estimate [36], where 24.2% of the population were using safely managed sanitation. The estimated 23.0% of the population using improved sanitation in 2018/19 was greater than the 2010 DHS [26], where 8.8% of the population were estimated to have used improved sanitation. However, it is much less than the reported level of access to improved sanitation reported by the 2015/16 DHS [17] and 2018 Census [19], which reported that 55.1% (83.7% including shared facilities) and 63.8% of the population were using improved sanitary facilities, respectively. To meet the Malawi 2063 target of 100%, the Government should prioritize a revision of the 2008 National Sanitation Policy [18] to guide investment and to set clear metrics for implementation and management.

The most common type of improved sanitary facility in all of the surveys was pit-latrines with slabs. Slabs are covers over the pit-latrine hole that limit the opening of the pit, thereby minimizing light and insects entering the pit [48]. Slabs are a significant driver of latrine cleanliness; it is recommended that pit-latrines have concrete slabs to enable easy cleaning [48,49]. The difference in the reported level of improved sanitation is primarily observed as a difference in the ratio of pit-latrines with and without slabs. The 2018 Census [19] and 2015/16

DHS [17] reported that the majority of pit-latrines had a slab, whilst the 2010 DHS [26] and 2018/19 CJF Survey presented here found that the majority of pit-latrines had no slab. There was a reduction in the percentage of pit-latrines with a slab from the 2015/16 DHS [17] to the 2018 Census [19], which indicated an overestimation of the proportion of pit-latrines with slabs in the 2015/16 DHS. The most common form of sanitary facility in the 2018 Census [19] was a pit-latrine with an earth/sand slab, with 83.2% of non-VIP pit-latrines with slabs having an earth/sand slab. It is recommended that pit-latrine slabs are made of concrete [48]. Therefore, it is likely other surveys misidentified a ’pit-latrine with slab’ and therefore assigned non-concreted facilities as an improved facility. If these were classed as unimproved facilities, rather than improved, 19.0% of sanitary facilities in the 2018 Census [19] would have been classed as improved (rather than 69.3%); this would be closer to the CJF Survey estimate in this paper (24.4%). Some of the discrepancies in the percentage of sanitary facilities classed as improved in the different surveys may therefore be due to whether pit-latrines with basic earth/sand slabs were classified as ’pit-latrines with slabs’ or were classified as not having a slab in different surveys. The national optics of having a higher proportion of sanitary facilities classified as improved should also be considered within these discrepancies.

The 2015 DHS [17] reported the lowest estimate of open defecation, with 5.4% of the population being reported as practicing open defecation. Meanwhile, the 2018 Census [19] provided a slightly higher estimation of open defecation, reporting 5.9% of the population practicing open defecation, which is similar to the 2020 UNICEF estimation of 6.0% of the population practicing open defecation [21]. This could be linked to an increased effort to reduce open defecation around the end of the millennium development goals in 2015 [47].

The trend in access to sanitary facilities was evaluated to project the future level of access for the population under multiple SSPs [24,25]. Assuming a linear trend in the rate of the expansion and development of sanitary infrastructure, the percentage of the population (non-linear growth) with access to sanitary facilities was calculated; none of the projections of population growth predict that Malawi can meet the aim *to end open defecation by 2030*, as outlined in SDG 6 [9]. UNICEF estimates that by 2030, less than 1% of the population will be practicing open defecation if the current annual rate of reduction in open defecation continues [4,6]. This is calculated through estimating the required annual rate of reduction in open defecation and comparing this to the annual rate of reduction in open defecation [6]. Given the rate of population growth in Malawi, it will require an *ever-increasing number* of sanitary facilities to be constructed each year for Malawi *to maintain the current rate* of open defecation reduction. This paper therefore investigated the current trend in the provision of sanitary facilities, rather than open defecation reduction, enabling the rapid increase in population to be accounted for.

SSP2 models 'business as usual' population growth [24] (Figure 5) and projects that Malawi will reach an end to open defecation (100% of the population having access to sanitary facilities) by 2060. The Government of Malawi outlined the goal of ensuring all households use 'safely managed sanitation' by 2060 [14]; at the current rate of development, Malawi looks likely to only end open defecation by this point, representing the minimum level of provision necessary for Malawi to meet this goal. Under the low population growth scenarios, SSP1 and 5 [24] (Figure 5), Malawi is projected to end open defecation before 2035. Meanwhile, under *high population growth scenarios*, SSP3 and 4 [24] (Figure 5), Malawi is projected to see *an increase in the level of open defecation* as the rate of the provision of sanitary facilities does not keep pace with the rate of population growth.

For Malawi to meet the international and national goals for sanitation provision, the rate of development of sanitary infrastructure will need to increase. Pit-latrines remain the primary sanitation system in Malawi, with 85.3% of the population using pit-latrines as their toilet facility [19]. We found that 99.4% of the 201,782 sanitary facilities surveyed were pit-latrines (including with/without slabs, as well as VIP latrines). Investing in the construction of pit-latrines has been critical in the Government of Malawi's strategy to work towards achieving the millennium development goal, Target 7.C: "By 2015 to halve the proportion of people without sustainable access to safe drinking water and basic sanitation" [48] and, more recently, the sustainable development goal 6 [9], "Achieving access to adequate and equitable sanitation and hygiene for all and ending open defecation by 2030". There has therefore been a significant increase in the population using pit-latrines in Malawi, largely driven by the reduction in people practicing open defecation. Whilst the associated reduction in open defecation has laudable benefits for public health and environmental management [48,50], pit-latrines also have the potential for negative health and environmental consequences if they are not managed effectively [51]. For example, pit-latrines can lead to both microbial and nutrient contamination of water resources [51–56]. Whilst pit-latrines provide a low-cost method of sanitation and are widely used in Malawi (and other countries), *there may be long-term consequences for Malawi's groundwater supplies from the construction of the sheer number of pit-latrines necessary to end open defecation and service Malawi's projected population increase*. Unless well considered and managed, the unrestrained expansion of pit-latrine construction to meet the needs of an ever-growing population may pose dangers to groundwater. There is a need to model the extent of the projected pit-latrine construction, according to the population growth patterns, to investigate contamination risks and ensure effective policy.

Another contamination risk from pit-latrines is through the deposition of non-human waste within pit-latrines. We found that 88.3% of latrines contained non-human waste. The most common non-human waste deposited in latrines was ashes (77.1%), commonly added to minimize smell [57,58]. Ash has also been suggested to have the additional benefit of minimizing groundwater contamination from pit-latrines [59]. Smell is an important consideration within the non-human waste deposited in latrines as there are reports of "disinfectants, pesticides, oil, laundry and soapy water, detergents, and car-battery acids" being added to reduce smell from latrines [58]. Indeed, *we found that 8.32% of pit-latrines had oil added*, which poses a considerable risk to the groundwater quality. The addition of this waste, rather than ash, has associated public health concerns [60]. There was also a significant proportion of pit-latrines (7.0% of cases) in which rubbish or plastic bags were deposited.

The construction of pit-latrines is not only necessary to meet the sanitary requirements of additional users (those either transitioning from open defecation or due to population growth), but also to maintain the needs of the pit-latrine-using population. This survey found that 111,377 of the 201,782 sanitary facilities were replacements for a previous latrine that had filled up. There is great variation in the literature regarding the time that pit-latrines are anticipated to last before they are filled [43,61–65]. We found that it typically took more than 3 years for pit-latrines to fill up; however, 40.8% of pit-latrines were found to have filled up in under 3 years. We estimated that there was an average of 6.5 pit-latrine users sharing a pit-latrine. Overall, 51.7% of the respondents reported that the latrine was used by 5 or less users, with 39.7% reporting having 6–10 users. Malawi has an average household size of 4.5, suggesting that approximately half of pit-latrines were used by 1 household only. The amount of time taken for the pit-latrine to fill did not show a statistically significant correlation with the number of pit-latrine users; this may be because pit-latrines are constructed in accordance with the number of intended users. There is significant variation in the estimates of how long pit-latrines take to fill up, with estimates varying from 3 months to over 26 years. The estimates of pits filling within a matter of months are typically cases where the pit-latrine has been constructed too small. Pit-latrines may be constructed too small either intentionally, when applying the ‘Arboloo’ method of constructing a deliberatively small latrine for use for 3 months to 2 years that is then covered in soil and a tree planted on top [66], or due to the latrine being an insufficient size for the number of users [67]. On the other hand, higher estimates vary from around 15 years [46,47] to reports of pit-latrines taking over 26 years to fill [43]. We calculated an average of 8.0 years for pit-latrines to fill up, which agrees with the average estimate of approximately 8 years provided in Brouckaert et al., 2012 [47].

Pit-latrine filling was found to be a major reason for pit-latrines being abandoned and new latrines being constructed (30.2% of cases). This is supported by findings in the literature [48,63]. We estimated that under the current rates of new latrine construction and level of pit-latrine usage and applying our estimates of the number of people who share a pit-latrine and the rate of pit-filling, *between 2020 and 2070, there would be 31.8 million pit-latrines constructed and abandoned due to filling up*. This represents a significant financial investment in sanitation infrastructure that would be abandoned, as well as presenting a challenge in providing space for the safe construction of new pit-latrines. The replacement of pit-latrines also causes delays in access to sanitation facilities whilst users find resources to build replacement latrines [18]. The concept of 'Stranded Assets' [37] should be considered here to guide a more sustainable sanitation investment strategy following a revision of the 2008 National Sanitation Policy [18], given that pit-latrine 'assets' are ultimately converted to a social, environmental, and financial liability through abandonment.

In the current 'business as usual' Sanitation Policy, Malawi's government must ensure a high level of pit-latrine construction, not simply to account for the growing population and a transition away from open defecation, but also to service a sanitation system that is reliant on regular replacements. Techniques such as pit-latrine emptying have the potential to expand the lifespan of pit-latrines, thereby limiting the pit-latrine construction needed to simply replenish the existing stock [68]. Further research will be necessary to evaluate the feasibility of such techniques being economically viable solutions to this problem.

There is also a significant issue with pit-latrine collapse, with 55.7% of latrines being abandoned due to collapse and 59.2% of latrines being replacements for a previously collapsed latrine. To ensure pit-latrine longevity, and thereby further minimize the necessary replacement construction, designs to minimize the collapse of latrines, such as promoting the lining of latrines [68], should be further explored. Another challenge of pit-latrine abandonment and collapse is managing disused latrines. Best practice for decommissioning latrines stipulates that the latrine superstructure should be dismantled, the latrine should be filled and lime added to kill pathogens, and the latrine should be covered with debris piled on top [69]. However, we found that 58.4% of decommissioned latrines had no decommissioning process whatsoever, presenting a public health risk through human waste remaining exposed.

This work aimed to provide a large-scale, comprehensive overview of sanitary facility access within Malawi. The use of the CJF Survey enabled an overview of a substantial dataset of over 200,000 latrines; however, as it did not survey every sanitary facility in Malawi, some may suggest that there is a bias towards latrines that were more accessible to the surveyors. Furthermore, whilst we provide a summary of the types of sanitary facilities used across Malawi, it was beyond the scope of this study to explore the behavioural and cultural dynaMICS of sanitary facility usage.

Therefore, whilst we evaluate the potential access to sanitary facilities, we are unable to accurately evaluate the nature of the usage of each facility type. This is a particularly important consideration when evaluating the extent of open defecation as open defecation can still be observed when sanitary facilities are available [70–72].

Further work would be beneficial to explore how open defecation can be eradicated within Malawi, not only from the perspective of sanitary facility access, but also regarding community-wide cultural and behavioural change [72,73]. For the purposes of this study, we assume a linear trend into the annual growth in sanitary access and applied this alongside non-linear population growth models to estimate the number of people with sanitary facility access annually. The use of a linear model was applied given the current data on national open defecation available for consideration. However, it should be noted that the future levels of sanitary facilities access projected over this time period within this work may not follow such a model; the level of sanitary facility provision is highly influenced by multiple socioeconomic and policy factors, which would significantly impact the projected levels of open defecation summarized within this work.

Based on the findings of this work, we suggest several policy recommendations to ensure Malawi can take the necessary steps to end open defecation, which is necessary for Malawi to achieve SDG6.2.

(1) For Malawi to achieve an end to open defecation, a review and revision of the 2008 National Sanitation Policy [18] is critical to set standards, guide investment, prescribe metrics, and management targets to meet the Malawi 2063 aim of 100% coverage.

(2) A revision of the 2008 National Sanitation Policy [18] should also take into account the critical need to move away from the approach of 'Stranded Assets' (investment in sanitation infrastructure, mainly pit-latrines, as a solution) and guide investment in sustainable and longer-term waste strategies.

(3) Finally, a revision of the 2008 National Sanitation Policy should guide disruptive change in third-sector strategies, moving them from short-term solutions (pit-latrines) to longer-term sustainable sanitation investment for social, environmental, and economic good.

5. Conclusions

The survey presented in this paper, evaluating over 200,000 sanitary facilities, found an estimate of *only 24.2% of these facilities were classed as improved*, which is significantly lower than the 88.5% in the 2015/16 DHS [17] and the 69.3% in the 2018 Malawi Census [19]. We also evaluated Malawi's progress in ending open defecation by projecting the rate of the provision of access to sanitary facilities alongside the projected population growth under multiple socioeconomic scenarios. *At the current rate of sanitary provision, no population growth scenario projected that Malawi will be able to meet SDG 6 and achieve an end to open defecation by 2030*. The non-linear SSP2 model, representing 'business as usual', only projects an end to open defecation by 2060.

To meet SDG 6 under the current population growth, providing safe and accessible sanitation to all will need an ever-increasing rate of sanitary investment and provision. Furthermore, focus is needed to ensure that sanitary facilities are not just able to meet the requirements of basic sanitation, but rather, an increased quality of investment is necessary to eliminate stranded assets and ensure an increasing proportion of the population has access to improved sanitary facilities. It may also be wise to review the 2008 National Sanitation Policy

[18] to also consider the risks to groundwater posed by the scale of pit-latrine-use and the resulting growth of point source human and non-human contaminant sources. Finally, there is a need for policy-set metrics to closely follow trends and for long-term modelling of sanitation requirements in order to meet the Malawi 2063 targets without stumbling into unintended consequences.

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Institutional Review Board Statement: This study followed the ethical guidance of the Government of Malawi.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. All data collected were in line with the Government of Malawi ethics and was agreed with each participant.

Data Availability Statement: Confidential data were obtained from the Government of Malawi. Additional data were obtained from publicly surveys including US Aid Demographic Health Surveys (DHS) Government of Malawi Census Data and US Aid Malaria Indicator Surveys (MIS).

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Appendix A

Table A1. Raw data of the total number of pit-latrine users and time taken for the pit-latrine to fill.

Time to Fill Up	1–5 Users	6–10 Users	11–20 Users	More Than 20 Users	Total
More than 3years	28,590	22,054	2375	2957	55,976
2–3 years	10,442	7967	781	563	19,753
1–2 years	5103	4023	426	279	9831
6 months–1 year	1307	903	126	76	2412
Under 6 months	238	155	17	13	423
Total	45,680	35,102	3725	3888	88,395

Conducting a two-factor ANOVA without replication of the data (Table A1 Appendix A) results in a *p*-value for the variance in columns (the number of users) of 0.063464 (not statically significant). The F-value for the variance in columns (number of users) was 3.175501432, which is less than the critical F value of 3.490294819. The number of users does not have a significant effect on the time taken for the latrine to fill.

Appendix B

The trend in the number of people being given access to sanitary facilities each year is shown below. The upper and lower confidence intervals are shown in grey lines, with the data points in blue dots. The trend has a *p* value of 0.00927 (3 significant figures) and is therefore classed as a significant trend.

The fit has a residual standard error: 0.1319 on 25 degrees of freedom. Multiple R-squared: 0.2413, Adjusted R-squared: 0.2109 F-statistic: 7.95 on 1 and 25 DF, and a *p*-value: 0.009273.

The minimum residual is −0.301877. First Quintile is −0.035110. Median residual is -0.006725. Third Quintile is 0.067085. The maximum residual is 0.260931.

Table A2. Summary of the coefficients of the trend shown in Figure A1 Appendix B. Significance codes are codes: ‘**’ 0.001, ‘*’ 0.01.

	Estimate	Std. Error	T Value	Pr(>|t|)
(Intercept)	−18.066851	6.535636	−2.764	0.01055 *
year	0.009191	0.003260	2.820	0.00927 **

Figure A1. Upper and lower confidence intervals are shown in grey lines. Data points are shown as blue dots and the trend is shown as a red trend line.

Appendix C

Table A3. Weighted average of amount of time to fill the pit-latrine. Upper bound of 20 years for ‘more than 3 years’ was based on literature estimates [42,43]. The weighted average was calculated by multiplying the percentage of responses with the average number of years taken to fill the pit-latrine in each time bracket and summing responses for each bracket.

Time to Fill Up	Lower Bound (Years)	Upper Bound (Years)	Average (Years)	Percentage of Responses	Weighted Average (Years)
Under 6 months	0.0	0.5	0.25	0.479	0.00120
6 months–1 year	0.5	1.0	0.75	2.73	0.0205
1–2 years	1.0	2.0	1.5	11.1	0.167
2–3 years	2.0	3.0	2.5	22.3	0.559
More than 3 years	3.0	20	11.5	63.3	7.28
					8.03

Table A4 Weighted average number of pit-latrine user. The weighted average number of users for each bracket was calculated as the product of the percentage of responses in that bracket and the average number of users, the weighted averages for each bracket were summed to give a total weighted average.

Time to Fill Up	Lower Bound (Users)	Upper Bound (Users)	Average (Users)	Percentage of Responses	Weighted Average (Users)
1–5 users	1.0	5.0	3.0	51.7	1.55
6–10 users	6.0	10.0	8.0	39.7	3.18
11–20 users	11.0	20.0	15.5	4.21	0.653
More than 21 users	21.0	30.0	25.5	4.40	1.12
					6.50

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6.2.1 Postface

This piece answered RQ3 ‘What are the challenges to sanitation and hygiene in Malawi?’ by addressing SO7 and SO8. Specifically, the piece utilised a large dataset of sanitary infrastructure to assess the current provision of sanitation. The work identified a challenge in attaining SDG6.2 in the inadequate provision of improved sanitation with most sanitary facilities being pit-latrines without slabs. The piece then addressed SO8 by predicting future sanitation provision in Malawi. The chapter answered RQ3 by identifying the expanding requirements of a growing population as a major challenge to Malawi’s sanitation infrastructure development. The work concluded that, at current rates of development, under all current scenarios of population growth, Malawi is not on track to end open defecation by 2030 as set out by SDG6.2. Some population growth scenarios project an increase in open defecation as the provision of sanitation is unable to keep pace with population growth. The current major sanitary infrastructure of pit-latrine usage also poses a growing threat to environmental health with a projection that 60 million pit-latrines will be filled and abandoned by 2070. Reaching SDG6.2 will require a significant increase in the rate of sanitary provision whilst ensuring appropriate pit-latrine usage.

SO9 recognises that progress to SDG6.2 also requires consideration of the sustainability of improvements in sanitation provision. The high frequency of pit-latrine replacement due to filling up and collapse raises a risk that hard-won progress in the provision of sanitation improvements may be short lived; the resultant loss of sanitation infrastructure can result in a return to open defecation and slippage in progress to SDG6. This is directly addressed within the next paper.

In addition, progress in hygiene is also central to achieving SDG6, not only in meeting SDG6.2 which focuses on sanitation provision, but also intersecting with safe water provision. Inadequate hygiene can undermine clean water provision, notably in the proliferation of waterborne disease (Eshcol et al., 2009) and can undermine improvements in sanitation access.

The challenges of ensuring adequate hygiene provision alongside sustainable sanitation are the subject of SO10 and are discussed within the next paper.

6.3 Progress and slippage of sanitation and hygiene targets in Malawi: is SDG6.2 achievable?

Rebekah G.K. Hinton[1, 2*], Laurent-Charles Tremblay-Lévesque[3, 4], Christopher J.A. Macleod[2], Mads Troldborg[2], Modesta Kanjaye[5], Robert M. Kalin[1]

[1] Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow UK; Rebekah.hinton@strath.ac.uk (R.G.K.H.); Robert.Kalin@strath.ac.uk (R.M.K.)

[2] The James Hutton Institute, Craigiebuckler, Aberdeen AB15 8QH, UK; kit.macleod@hutton.ac.uk (C.J.A.M.); mads.troldborg@hutton.ac.uk (M.T.)

[3] Global Water Partnership, PO Box 24177, SE-104 51, Stockholm, Sweden; laurentcharles.tremblaylevesque@gwp.org (L.C.T.L)

[4] Sociology of Development and Change Group, Wageningen University & Research, P.O. Box 8130 6700 EW Wageningen, Netherlands

[5] Director of Sanitation, Ministry of Water and Sanitation, Government of Malawi, Private Bag 390, Lilongwe, Malawi; modesta.banda@gmail.com M.K.))

* Correspondance : Rebekah.hinton@strath.ac.uk;

Abstract: Sustainable Development Goal (SDG) 6 aims to achieve “access to adequate and equitable sanitation and hygiene for all and end open defecation” by 2030. We present an in-depth investigation of sanitation and hygiene practices of 939 Malawian households in 2 Districts, previously declared open defecation free (ODF). We evaluated if ODF status was maintained by evaluating access to sanitation and hygiene. We found 17% returned to open defecation, and faeces were observed around 10% of the households. We suggest that ODF status is not enough; work is required to maintain progress and consideration of construction quality is critical. Another barrier to SDG6.2 was only 7.9% of households had handwashing facilities with soap and water, with soap as a major limitation. However, most households (82%) had soap available for washing suggesting that soap is not being prioritised in handwashing.

Keywords: Handwashing; Hygiene; Open Defecation; Sustainable Development Goals; Sanitation

Highlights:

1) ODF status was not maintained in 2 districts that had previously been declared ODF, evidence of slippage.
2) Sanitation facilities are not providing sufficient security, a particular challenge in meeting the sanitary requirements of women and girls.
3) There is a low level of access to handwashing facilities with soap and water (7.9%) with soap being the main barrier.
4) Low access to soap for handwashing may be due to insufficient prioritisation of soap for handwashing as 82% of households reported having soap available for washing.
5) We propose a shift from ‘intervention’ based investments to ‘managed investments’ and regular monitoring and reinvestment in sanitation and hygiene infrastructure.

1. Introduction

Access to sanitation and hygiene resources is a cornerstone of public health to limit diarrhoeal disease. The importance of sanitation and hygiene is emphasised in Sustainable Development Goal (SDG) 6 (UN General Assembly, 2015). SDG6.2 aims “by 2030, to achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations.” (UN General Assembly, 2015). To achieve SDG6, the rate of development in Water Sanitation and Hygiene (WASH) services in Africa needs to significantly increase, an estimated 20 and 42 times increase required to ensure access to safely managed sanitation basic hygiene services by 2030 (WHO and UNICEF, 2022). A lack of access to appropriate sanitation and hygiene facilities is a significant public health concern.

WASH provision is an essential component of controlling water-borne disease outbreaks and preventing deaths (Back et al. 2018, WHO, 2023). Women and children are disproportionately impacted by poor water, sanitation, and hygiene access (Ghosh & Sarkar, 2023; Wayland, 2019).

Women often risk sexual harassment when traveling to a defecation site (Cairncross *et al.*, 2010). Where private and separate sanitation facilities are supplied, school enrolment rates increase, and dropout rates decrease in pubescent and menstruating young women (Fischer, 2006).

Community Led Total Sanitation (CLTS) has been widely promoted to improve sanitation and hygiene practice. CLTS is a behavior change encompassing a series of participatory activities that communicate the negative consequences of open defecation (OD) taking action towards becoming open defecation free (ODF) (Chambers and Kar, 2008; Venkataramanan *et al.*, 2018, Tribbe et al., 2021) by encouraging communities to design and build their own sanitation facilities based on locally available materials and conditions. Additionally, CLTS is traditionally combined with a broader environmental hygiene component (Maulit, 2014). Initially promoted in Bangladesh in 1999, CLTS has since spread to countries across the world, mostly in Asia and Africa (Zuin et al., 2019). Whilst the concept of CLTS promotion is a global phenomenon, cultural and community perceptions of sanitation and hygiene practices are central in ensuing long-term and sustainable change (Tribble et al., 2021). Evaluating local level adoption of CLTS is therefore critical for effectively informing national level policy and practice alongside enriching global knowledge on the most effective promotion of sanitation and hygiene behaviour change. Ensuring long-term improvements in sanitation and hygiene provision requires consideration of the maintenance of progress made, alongside reduction in OD. Preventing communities slipping back to OD is a priority (Cavill *et al.*, 2015; Pasteur, 2017; Ngwale &DeGabriele, 2017). Slippage results from behavioural change and attitudes around OD, as well as damage to sanitary facilities from natural hazards and depreciation over time (Jerneck *et al.*, 2016).

Malawi has a high burden of inadequate sanitation and hygiene. Poor access to WASH is reported to contribute to the deaths of 3,000 children under five each year in Malawi (Moon *et al.*, 2019; Dinala *et al.*, 2020) and is a major factor in the high level of growth stunting and malnutrition (Doctor and Nkhana-Salimu, 2017). Insufficient sanitation has economic consequences; a 2012 report found that Malawi lost approximately $57 million from poor sanitation annually, accounting for 1.1% of national GDP in 2012 (Worldbank, 2012). CLTS was introduced in Malawi in 2008 and has since become a cornerstone of the government's strategy for promoting access to sanitation and hygiene (Ministry of Health and Population, 2018; Taulo *et al.,* 2018). The promotion of sanitation in Malawi, including through concerted CLTS efforts across the country, has resulted in over a 20% reduction in the percentage of the population practising OD from 1992 to 2018 (Hinton *et al.,* 2023). However, challenges remain to ensure the provision of sanitary facilities keeps pace with population growth (Hinton *et al.*, 2023). Furthermore, an increased frequency of extreme weather events under climate change will further threaten Malawi's WASH infrastructure (Otto *et al.,* 2022). As such, Malawi serves as a particularly pertinent context in which to examine the long-term sustainability and success of CLTS.

Alongside improving access to sanitation, CLTS encourages the adoption of improved hygiene practice. Handwashing is an effective intervention to reduce preventable child deaths and illness (Maulit, 2014). Handwashing with soap was linked to a 48% reduction in diarrhoeal disease (Cairncross *et al.*, 2010). Within Malawi, access to handwashing facilities with soap and water is low, with estimates that 8% of the population have access to a handwashing facility with soap and water (UNICEF, undated; WHO and UNICEF, 2021). This study investigates whether CLTS, resulting in ODF status, successfully increased handwashing access. Personal hygiene such as body and face washing also contributes to disease prevention (Bartram and Cairncross, 2010). Access to bath shelters/ bathrooms for bodily washing has not been widely documented in the Malawi Census, and DHS surveys (NSO 2018; NSO and Macro international, 2016) or in the Malawi Malaria Indicator Survey (MIS) (NMCP and ICF, 2018). Bathing is important not only for hygiene, but also cultural and religious practises (Rusca *et al.*, 2017). This study explores access to bathing facilities to develop a holistic picture of sanitation and hygiene access within Malawi.

The objective of this research was to examine the access to, and maintenance of, adequate and equitable sanitation and hygiene in Malawi. Focusing on case-studies that were previously declared ODF examines the danger of ODF slippage and the consequences for ensuring sustainable and long-term improvement to sanitation and hygiene (Tribble et al., 2019). Through a survey of over 900 households across two Districts in Malawi we examined access to both sanitation and hygiene facilities following CLTS intervention, investigating a range of metrics including provision of sanitation facilities, handwashing, and bathroom usage. We compare these results with data from DHS surveys (NSO and Macro international, 2016). We addressed the research questions: (1) What are the major limitations to ensuring equitable access to sanitation and hygiene in Malawi under SDG6.2 (UN General Assembly, 2015)?; (2) What are the challenges for maintaining progress to ensure continued access to sanitation and hygiene under SDG6.2 (UN General Assembly, 2015)?

2. Materials and Methods

2.1 Study area

Malawi is a country in South-Eastern Africa with a population of almost 20 million (NSO, 2022; World Bank data, undated). The population is rapidly growing, anticipated to reach 54 million by 2070 (Kc *et al.*, 2017; Riahi *et al.*, 2017). The Government of Malawi estimated in 2020 the percentage of the population with access to safely managed sanitation was 35.2%, with a development plan to reach 100% access by 2060 (NPC, 2020). In 2020, it was estimated that 65.5% of the urban population had access to safely managed sanitation services, the Government aims to reach 100% by 2042 (NPC,2020). This necessitates significant investment in sanitation infrastructure (Hinton *et al.*, 2023).

The current population of Malawi is predominantly rural, with 17.1% in urban areas in 2019 (NPC, 2020). Malawi's development plan (NPC, 2020) anticipates that by 2063, 60% of the population will be living in urban settings. A large proportion of the urban population resides in informal settlements with inadequate housing; 60% recorded as living within slums in 2020 (NPC, 2020). The Government of Malawi aims to reduce this to 10% by 2063 (NPC, 2020).

Progress has been made ending OD in Malawi (Hinton *et al.*, 2023). The Ministry of Health classifies traditional authorities as 'Open Defecation Free' (ODF) if they evidence having eliminated OD within the entire sub-district region. By 2021, over 138 traditional authorities reported to have achieved ODF status (Nzangaya, 2021). This study focuses on assessing the sanitation and hygiene status in two Districts of Malawi Districts A and B (references withheld for anonymity purposes). Both Districts have undergone several waves of CLTS programming before being declared ODF in 2018.

2.2 Study design

Household surveys were conducted between the 5th and 25th of July 2019. Surveys were conducted in Districts A and B drawing from the cluster sampling strategy used by the UNICEF Multiple Indicator Cluster Surveys (UNICEF, 1995). The first step was to select, in consultation with the District Environmental Health Officers, and the District Water Development Officers, a set of Health Facility service area of 10 Healthcare Centres (HCC), six in District A and four in District B. The next step was to divide the service area into smaller segments based on the population estimates from the group village heads (GVHs). Enumerators were then assigned different starting points within these clusters and requested to select consecutive households until their assigned individual quota was reached. In total, 733 households in District A and 206 households in District B were surveyed; this equates to less than 1% of households across the two Districts but represents a sizable proportion of the households in the GVHs directly surrounding the selected HCCs. For reference, the 2015/16 DHS survey reported on 0.66 percent of households relative to the number of households reported in the 2018 census (NSO, 2018, NSO and Macro international, 2016).

Households were interviewed using a questionnaire based on the Malawi ODF Status Assessment Form and core questions from the UNICEF-WHO Joint Monitoring Programme

Household Survey (WHO and UNICEF, undated). The interviews were conducted in Chichewa by trained NGO workers, in collaboration with District and Area Environmental Health Officers, and District Water Development Officers. Data was collected using mobile-based forms which were checked and validated. Some enumerators used paper forms before transferring the data onto the mobile form. To ensure data validity, interviewers were given a list of observations, which they used to confirm the responses from the interviewee (e.g., visit the handwashing station to collect evidence of use of soap, paying attention to the wetness of the area, presence of soap, and absence of web or dust). Random spot checks were also conducted by researchers to ensure consistency in the interviewers recorded information. Informed verbal consent of study participants was obtained prior to participation. Before proceeding with the questionnaire, the interviewers provided background information on the survey (e.g., objectives, anonymity, length of the interview, etc.) and specified that the respondent could decide to not respond, skip a question, or stop the interview at any time.

2.3 Data analysis

Data sets were cleaned to remove duplicate responses and any surveys conducted outside of the specified survey window. The percentage of the population with access to handwashing, sanitary, and bathroom facilities was calculated. Where available, this data was compared to the Government of Malawi estimates from DHS (NSO and Macro International, 2016) reports. Field observations, thick description, and quotes were used for triangulation purposes (Creswell and Clark, 2004).

3. Results

3.1 Open defecation and toilet provision

The level and type of sanitary provision was compared to official Government of Malawi census estimations, Table 1. District A and B reported that pit-latrines without concrete slabs were the most common type of sanitary facility (76.5% and 76.7% in District A and B, respectively). Both Districts reported below 1% of the population using flush toilets, eco-toilets, or other forms of sanitary facilities. The second most commonly listed sanitary facility was households with no sanitary facility/ practising OD. District A reported a higher level of OD (17.6%) than District B (12.6%); both higher than the 2018 Census estimations of 6.1% and 5.2% for Districts A and B, respectively. District A reported 4.8% and District B reported 10.7% of the population using pit-latrines with concrete slabs.

Table 1: Survey results for the presence and type of sanitary facilities used by households in District A and B compared to the Government of Malawi 2018 Census (NSO, 2018).

	Percentage of households with sanitary facility (%)			
Type of sanitary facility	District A 2019	District B 2019	Census 2018 District A	Census 2018 District B
Flush toilet	0.1	0.00	0.7	0.5
Pit-latrine With concrete slab	4.8	10.7	5.4	4.5
Pit-latrine without concrete slab	76.5	76.7	80.7	84.6
Eco-toilet/ composite	0.8	0	4.6	3.5
Other	0.1	0	2.6	1.7
None/ Open defecation	17.6	12.6	6.1	5.2

Observation of faeces was an indication of OD. District A reported that 71 households (9.7%) had observable faeces whilst District B reported that 27 households (13.1%) had observable faeces. The percentage of households with observable faeces around the property was higher than the 2018 Census estimation for OD.

The nature of the sanitary facility was evaluated to determine whether sufficient privacy and security were provided by sanitary facilities, Figure 1. 62.3% of facilities in District A offered privacy, 22.8% offered security, 67.0% had a roof, 18.7% offered both privacy and security, and 16.5% offered privacy and security whilst also having a roof. District B reported that 64.1% of facilities offered privacy, 32.0% offered security, 61.7% had a roof, 30.1% offered both privacy and security, and 24.3% offered privacy and security whilst also having a roof. The nature of the construction of the facility by the District and Healthcare Centre is summarised in Figure 1. Within District A, 22.5% households reported the sanitary facility was shared with other households, 59.6% reported it was not shared and 17.9% gave no response. Within District B, 18.9% households reported the sanitary facility was shared, 67.5% reported that the facility was not shared and 13.6% provided no response.

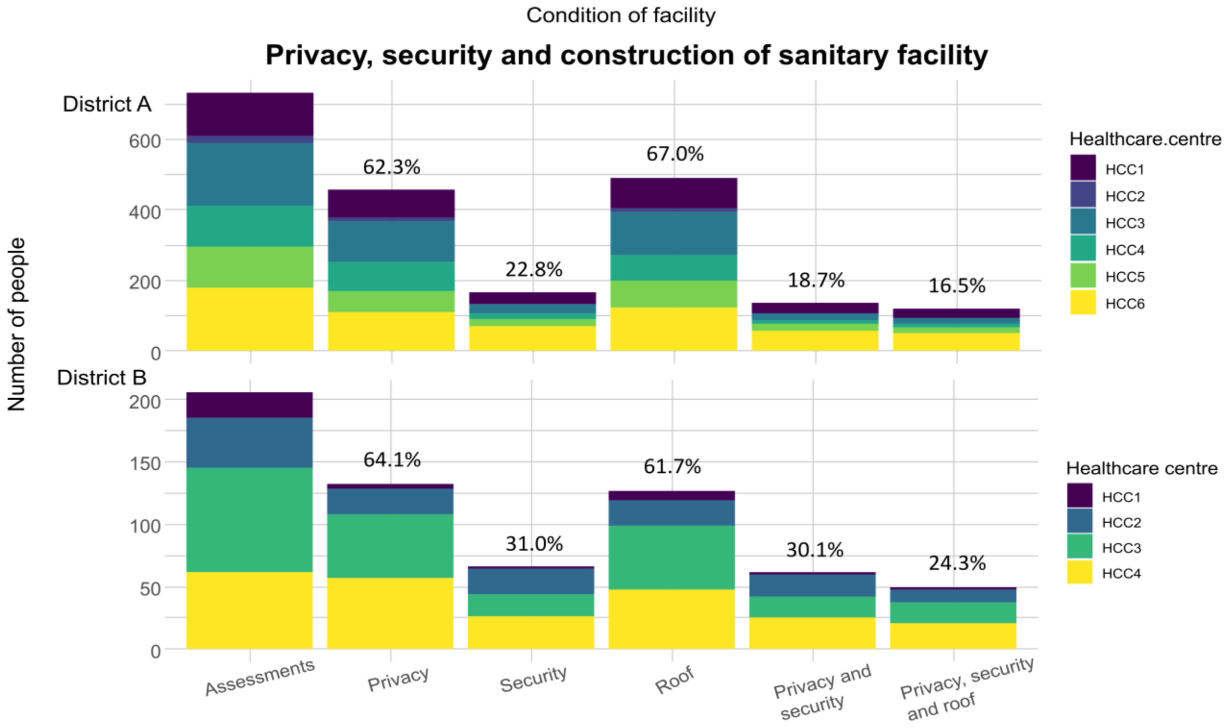

Figure 1: The number of households using sanitary facilities providing privacy, security and with a roof in district A and B. The Healthcare Centre (HCC) households were surrounding is also shown.

3.2 Handwashing facilities

Households were surveyed to determine whether a handwashing facility was available. Figure 2 summarises the number of households surveyed and the number of people with access to handwashing facilities. A summary of the data is found in the Supplementary Material, Tables A and B. Table 2 summarises the access to handwashing facilities and comparison to the DHS 2015/16 data. In District A 733 households were surveyed whilst 206 households were surveyed in District B. The 2015/16 DHS survey (NSO and Macro international, 2016) observed 1,179 and 473 households in District A and B respectively. The access to handwashing facilities and cleansing agents was summarised. Cleansing agents other than soap included locally available materials such as ash, mud, and sand.

*Table 2: The extent of households with handwashing facilities in district A and B from the survey presented in the paper and the 2015/16 Government of Malawi DHS survey (NSO and Macro International, 2016). *Facility within 10 paces from the nearest sanitation provision*

	Number of households with facility*		Percent of households with facility (%)*			
Type of facility	District A 2019	District B 2019	District A 2019	District B 2019	District A DHS 2015/16 Survey	District B DHS 2015/16 Survey
Hand washing facility	186	66	25.4	32.0	84.9	78.9
Handwashing facility with water	112	51	15.3	24.8	37.5	23.1
Handwashing facility with soap	53	26	7.23	12.6	6.9	4.0
Handwashing facility with water and soap	48	26	6.55	12.6	6.4	3.1

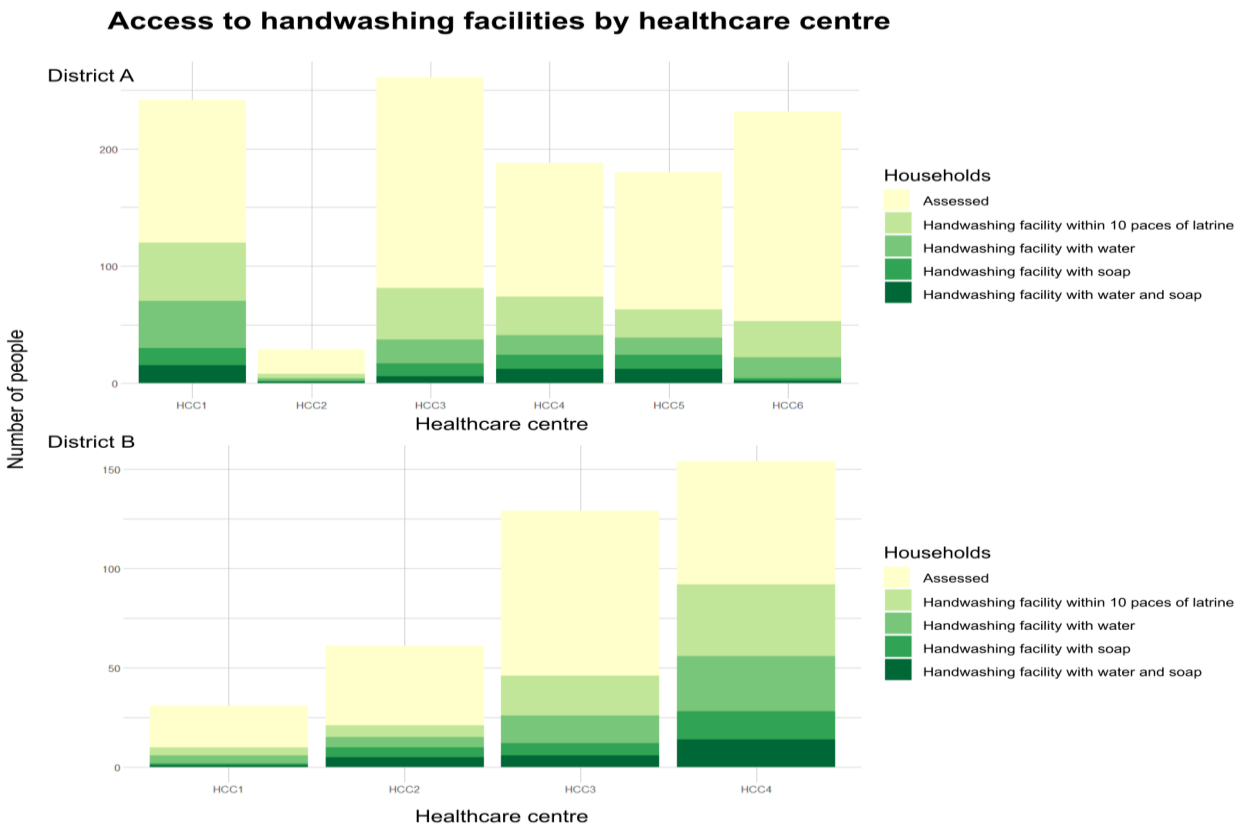

Figure 2: The access to handwashing facilities at households surrounding Healthcare Centres (HCC) in Districts A and B. Households were assessed for the presence of handwashing facilities within 10 paces of a sanitary facility/ latrine and the provision of soap and water at facilities.

3.3 Washing/Bathroom usage

The access to washing/bathroom facilities by households (733 in District A and 206 in District B) is summarised in Table 3. Overall, 91.9% (863) of households had a washing/bathroom facility. The use, facilities and level of privacy and security of all facilities was evaluated.

Table 3: The provision of bathroom facilities in Districts A and B.

	No. households with facility		Percentage of households with facility (%)	
Facility	District A 2019	District B 2019	District A 2019	District B 2019
Bathroom facility	675	188	92.1	91.3
Evidence being used	653	170	89.1	82.5
Sufficient water for bathing	563	178	76.8	86.4
Soap available	628	139	85.7	67.5
Bathroom offer privacy	518	138	70.7	67.0
Bathroom offer security	175	61	23.9	29.6

4. Discussion

OD is a major public health risk (Chambers and Kar, 2008), significant investment has been undertaken in Malawi to successfully reduce the level of OD (Hinton *et al.,* 2023). CLTS has been adopted as one of the techniques to promote improvements in sanitation and hygiene, and reduce OD, on a community level, recognising the community-wide implications of poor sanitation and hygiene. The significance of whole community access to sanitary facilities was echoed by stakeholders: "The number of households with no toilets is still significant though is a small figure. Water sources will still be contaminated because members from those households will still be defecating in the bush." (Personal Communication 18/03/2019). Through a CLTS programme, behavioural change and structural improvements can result in communities reaching ‘Open Defecation Free’ (ODF) status. However, the challenges of a meeting the sanitary requirements of a growing population make consideration of how OD improvements are maintained just as important as continuing with progress to eliminate OD. In this survey of 939 households that had previously been declared ODF, 17% were reported to now have no toilets/ practising OD and faeces were around observed around 10% of households. ***This suggests that improvements in ending OD have been short-lived and slippage should be monitored on a regular basis*** (Haq and Bode, 2008; Starkl *et al.*, 2013, Chambers and Kar, 2008). Rejection of sanitation infrastructure can contribute to slippage in OD, with constructed latrines not being used (Gupta *et al.,* 2016). This is particularly the case for children who may be fear of a child falling into latrine pits (personal correspondence; Chinoko, 2023). High rates of latrine collapse further emphasise the significance of infrastructure maintenance and appropriate construction (Hinton *et al.,* 2023; Kalumbi *et al.,* 2020). The consequence of latrine collapse was emphasised in communication with stakeholders; “Some toilets collapsed due to heavy rain which puts [leaves] some household to have no toilets” Personal communication (18/03/2019).

To minimise the risk of collapse, as well as improve hygiene, the Government of Malawi National Policy recommends that pit-latrines are fitted with a concrete slab (Nakagiri *et al.*, 2015). SDG target 6.2 (UN General Assembly, 2015) specifies access to an “improved” sanitation facility. This includes flush-latrines (to piped sewer systems or septic tanks), Ventilated Improved Pit-latrines (VIP), pit-latrines with a slab and composting/ composite toilets (World Bank Databank, undated) (NSO and Macro International, 2011). We observed that in both districts there were more households with no access to sanitation facilities than households with sanitary facilities constructed to the recommended standard to meet SDG6.2 ; 5.7% of households in district A and 10.7% in district B had access to sanitary facilities that would be classed as improved whilst 17.6% and 12.6% had no sanitary facilities in district A and B respectively. The level of access to improved sanitation is consistent with other studies in Malawi (Hinton *et al*., 2023; NSO 2018; NSO and Macro international, 2016; World Bank Databank, undated). Furthermore, SDG6.2

specifies for sanitary facilities to be a private (non-shared) facility (UN General Assembly, 2015; Hutton and Chase, 2016). Many of the households surveyed were observed to be sharing facilities with neighbours or facilities (such as schools), thus not meeting SDG6.2. Poor construction quality and inadequate maintenance of sanitary infrastructure threaten Malawi's progress to meeting SDG6.2 with many of the available sanitary facilities at high risk of collapse, thereby resulting in high risks of ODF slippage. Recognising sanitary interventions as long-term investments (WaterAid, 2021) is required to increase investment into high-quality sanitation infrastructure and, alongside behaviour change, improve the long-term sustainability of progress to SDG6.2.

Meeting SDG6.2 also involves consideration of meeting "the needs of women and girls and those in vulnerable situations" in sanitary and hygiene provision (UN General Assembly, 2015). Women and girls are at particular risk where inappropriate privacy and security is provided in sanitary and hygiene facilities (Fischer, 2006, Wayland 2019). As such, we evaluate the level of privacy and security of both bathroom and latrine facilities were evaluated. The majority of households had use of bathroom and latrine facilities offering privacy (70% of bathrooms and 63% of latrines), whilst fewer households had facilities offering security (25% of bathrooms and latrines). Ensuring facilties are constructed with appropriate security and privacy must be another construction consideration in meeting SDG6.2

Hygiene practice is an important investigation in evaluating progress to SDG6.2 Handwashing is a central hygiene practice, providing a simple, cost-effective method of limiting the spread of infectious diseases (Freeman *et al.*, 2014); handwashing with soap can reduce diarrhoeal disease risk by 42-47% (Curtis and Cairncross, 2003). However, progress on handwashing has been particularly lacking in Sub-Saharan Africa, according to the World Health Organisation (WHO) if a step change in progress is not achieved, Sub-Saharan Africa could end the 15-year SDG period (2030) with the same access to hand hygiene as they started (WHO and UNICEF, 2021). It is a challenge to quantify the level of handwashing; asking people if they wash their hands has been shown to be an ineffective measure of handwashing practice (WHO and UNICEF, 2021), rather measures of handwashing report the existence of adequate handwashing facilities with soap in households (UN, 2018; WHO and UNICEF, 2021). SDG6 indicator 2.1b reports on the availability of handwashing facilities, specifically measuring 'the proportion of the population with handwashing facilities with soap and water at home' (UN, 2018).

Our results support previous studies on handwashing access in Malawi. Overall, 27% of households had access to handwashing facilities within 10 paces of a latrine; this is similar to the DHS2015/16 Survey which estimated that 20% of households were reported to have a **fixed** handwashing facility whilst 63% were reported as having mobile handwashing facilities in the DHS 2015/16 survey (NSO and Macro International 2016).

To achieve a basic service level of hygiene, households require access to a handwashing facility with soap and water (WHO and UNICEF, 2021). Overall, only 7.9% of households met this basic service level of hygiene, a similar level to the DHS 2015/16 survey (NSO and Macro International, 2016), with soap being a major limiting factor in appropriate handwashing facilities.

Another facet of hygiene is access to washing facilities and bathrooms. We consider bathrooms as spaces used for washing, often (though not necessarily) separate from latrine facilities. Having access to adequate bathroom facilities for washing is not a defined indicator under SDG6.2, and is as-such less reported than other facets of sanitation and hygiene, but is important in ensuring access to adequate hygiene (with significant cultural and social weight) (Rusca *et al.*, 2017). Overall, 92% of households reported having a bathroom facility with 79% and and 82% of households having sufficient water and soap for bathing respectively. The high availability of soap for use in bathing is particularly stark when contrasted with the limited availability of soap in handwashing; 8.5% of households surveyed had handwashing facilities with soap. This suggests that access to soap is not the only limitation to soap usage in handwashing.

The prioritisation of water and soap resources for handwashing and bathing should be considered within the social, cultural, and religious context (Kalumbi *et al.*, 2020; Mtungila and Chipofya, 2009; Rusca *et al.*, 2017). A survey of hygiene practises in Malawi found that 24% and 11% of people ranked bathing and handwashing as the most important hygiene practise respectively (Rusca *et al.*, 2017). Similarly, treated water was the most common type of water used for bathing, untreated water was mostly used in handwashing (Rusca *et al.*, 2017). Our results suggest that bathing may be a greater priority for resource use (soap) than handwashing, despite the hygienic significance of handwashing. It is worth noting that both Districts surveyed within this study are majority Christian (NSO, 2018). Previous studies within Malawi have highlighted the differences in attitudes to hygiene amongst religious groups in Malawi (Kalumbi *et al.*, 2020; Rusca *et al.*, 2017) with some indication of a higher emphasis on bathing practises within Muslim than Christian communities (Rusca *et al.*, 2017). Bathing may also be a greater priority for soap usage due to its importance in the appearance of cleanliness. Rusca (2017) observed that "Everyday hygiene practices are pursued as means to project an image that is often equated with dignity and considered part of good citizenship. The fear of appearing dirty or unclean is a strong motivation for households to prioritize certain practices over others. This is particularly evident for brushing teeth, doing laundry, cleaning the surroundings of the house, and bathing" (Rusca *et al.*, 2017). Progress towards SDG6.2 in promoting soap use in handwashing should not only increase access to soap, but also highlight the importance of such hygiene practices.

The Government of Malawi is currently reviewing its Sanitation Policy through the new Ministry of Water and Sanitation. This offers a unique opportunity to reflect on published work and metrics from the past 2 decades and set new vision and direction to address the challenges of SDG6 and Malawi 2063. Given many of the rural investments by the third sector have been 'project based', it may be wise to consider policy interventions that guide the third sector to move away from 'intervention' based investments to 'managed investments' (WaterAid, 2021) and regular monitoring and reinvestment. There is also a need to consider governance structures that will enhance routine monitoring and management by Local or District municipalities, maintenance of existing infrastructure to reduce stranded investments (Kalin *et al.* 2019), and perhaps Sanitation and Hygiene management partnerships that might include co-investment support by the third sector or donors.

5. Conclusions

For Malawi to reach SDG6.2, "access to adequate and equitable sanitation and hygiene, and to end opening defecation", many facets of sanitation and hygiene must be implemented together, with on-going efforts to make sure gains are not lost whilst access is also improved (Hinton *et al.*, 2023). To evaluate progress and slippage in the path to SDG6.2, we evaluated over 900 households in 2 communities previously declared ODF, we observed that 17% of the population had no access to sanitary facilities or were practising OD. ***This suggests that communities that have previously been declared ODF may not be able to maintain this status without continuing support.*** Particular attention should be paid to ensuring appropriate construction of sanitary infrastructure to minimise the risk of collapse.

Whilst we estimated that only 8.5% of households had handwashing facilities with soap, we found that soap was available in bathrooms/ washrooms of 82% of households, suggesting soap was not prioritised for handwashing. To improve the level of basic hygiene, promoting a culture of handwashing with soap, alongside improving access, must be a key priority (Curtis *et al.*, 2001; Jumaa, 2005; Whitby *et al.*, 2007). A more in-depth barrier analysis will be necessary to truly understand the limitation to handwashing practises in Malawi and work to deconstruct such barriers.

SDG6.2 also specifies that sanitation and hygiene facility access should pay special attention to the needs of women and girls and those in vulnerable situations (UN General Assembly, 2015). Ensuring provision of sanitary and hygiene facilities with appropriate privacy and security is a particularly important factor in access to sanitation and hygiene for women and girls (Cairncross *et al.*, 2010; Fischer *et al.*, 2006; Hulland *et al.*, 2015; Raj *et al.*, 2019). The minority of households had use of bathroom and latrine facilities offering security (25% of bathrooms and latrines). Challenges of security and privacy must be considered in sanitary provision and construction.

The current review of the Government of Malawi Sanitation Policy offers a unique opportunity to address the challenges of SDG6 and Malawi 2063. New policy interventions may include a move by the third sector away from ‘intervention’ based investments to ‘managed investments’ with regular monitoring and reinvestment (WaterAid, 2021). New policy might also consider a need for mechanisms that enhance monitoring and management by Local or District municipalities, perhaps supported initially by the third sector or donors.

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Consent

Informed consent was obtained from all subjects involved in the study. All data collected was in line with the Government of Malawi ethics and was agreed with each participant.]

Data availability

Confidential data were provided by the Government of Malawi and CARE. All data summarised is provided here.Additional data was obtained from publicly surveys including US Aid

Demographic Health Surveys (DHS) Government of Malawi Census Data and US Aid Malaria Indicator Surveys (MIS).

Conflict of Interest

The authors have no competing interests to declare.

Abbreviations

NSO (National Statistical Office); DHS (Demographic Health Survey); HCC (Healthcare Centre); SDG (Sustainable Development Goal); MIS (Malaria Indicator Survey); WHO (World Health Organization); UNICEF (United National's Children's Fund); VIP (Ventilated Improved Pit-latrines); ODF (Open Defecation Free); (CLTS) Community Led Total Sanitation; WASH (Water Sanitation and Hygiene).

Supplementary Material

Supplementary Material Table A: The percentage of households surrounding key Healthcare Centers (HCC) in District A with handwashing facilities (within 10 paces of a latrine facility), water and soap.

District A	Percentage of households with hygiene facility (%)					
Facility	HCC1	HCC2	HCC3	HCC4	HCC5	HCC6
Handwashing facility within 10 paces of latrine	41.0	19.0	24.4	29.0	20.5	17.3
Handwashing facility with water	32.8	9.52	11.1	14.9	12.8	10.1
Handwashing facility with soap	12.3	4.76	6.11	10.5	10.3	1.13
Handwashing facility with water and soap	12.3	4.76	3.33	10.5	10.3	1.12

Supplementary Material Table B: The percentage of households surrounding key Healthcare Centers (HCC) in District B with handwashing facilities (within 10 paces of a latrine facility), water and soap.

District B	Percentage of households with hygiene facility (%)			
Facility	HCC1	HCC2	HCC3	HCC4
Handwashing facility within 10 paces of latrine	19.0	15.0	24.1	58.1
Handwashing facility with water	19.0	12.5	16.9	45.2
Handwashing facility with soap	4.76	12.5	7.23	22.6
Handwashing facility with water and soap	4.76	12.5	7.23	22.6

Supplementary Material Table C: Number of households with given sanitary facilities in District A and B

	Number of households with sanitary facility	
Type of sanitary facility	District A	District B
Flush toilet	1	0
Pit-latrine with concrete slab	35	22
Pit-latrine without concrete slab	561	158
Eco-toilet/ composite	6	0
Other	1	0
None/ Open defecation	129	26

Supplementary Material Table D: Number of households with sanitary facilities offering privacy, security, and a roof in Healthcare Centers in District A.

District A	Number of households with sanitary facility					
Facility	HCC1	HCC2	HCC3	HCC4	HCC5	HCC6
Total number of household assessments	122	21	180	114	117	179
Number of facilities that offer privacy	79	9	117	83	59	110
Number of facilities that offer security	33	0	26	17	20	71
Number of facilities with a roof	88	8	123	74	75	123
Number of facilities that offer privacy and security	29	0	20	12	19	57
Number of facilities that offer privacy and security and have a roof	26	0	19	9	18	49

Supplementary Material Table E: Number of households with sanitary facilities offering privacy, security, and a roof in Healthcare Centers in District B.

District B	Number of households with sanitary facility			
Facility	HCC1	HCC2	HCC3	HCC4
Total number of household assessments	21	40	83	62
Number of facilities that offer privacy	3`	21	51	57
Number of facilities that offer security	2	20	18	26
Number of facilities with a roof	8	20	51	48
Number of facilities that offer privacy and security	2	18	17	25
Number of facilities that offer privacy and security and have a roof	2	11	16	21

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6.3.1 Postface

This paper responded to RQ3 by exploring the provision of sanitary facilities in Malawi (SO8), identifying challenges in security and privacy in the provision of sanitary facilities which represent a particular challenge to meeting the needs of women and girls in sanitation access. The sustainability of sanitation provision was also considered, achieving SO9 and identifying a challenge of a return to open defecation in communities previously declared open defecation free. Hygiene provision alongside sanitary provision is also discussed, achieving part of SO10 by exploring levels of handwashing and bathing. The lack of prioritisation of soap in handwashing was identified as a challenge to hygiene provision in Malawi, answering RQ3. Steps to achieving SDG6.2 within Malawi will require a greater focus on sustainable sanitation progress alongside promotion of hand hygiene behaviour. Without concurrent improvement in all aspects, progress may be undermined and short-lived.

Achieving SDG6.2 requires that special attention should is paid to the needs of women and girls in meeting sanitation and hygiene targets. This work highlighted the challenges of ensuring privacy and security of sanitation and hygiene infrastructure towards this goal. Another key component to meeting the specific needs of women and girls in sanitation and hygiene provision is consideration of Menstrual Hygiene Management (MHM).

The next piece addresses SO10 focusing on Menstrual Hygiene Management (MHM).

6.4 Menstrual hygiene management in two districts of Malawi

Rebekah G.K. Hinton[1, 2*], Laurent-Charles Tremblay-Lévesque[3],[4] Modesta Kanjaye[5], Christopher J.A. Macleod[2], Mads Troldborg[2], Robert M. Kalin[1]

[1] Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow UK; Rebekah.hinton@strath.ac.uk (R.G.K.H.); Robert.Kalin@strath.ac.uk (R.M.K.)
[2] The James Hutton Institute, Craigiebuckler, Aberdeen AB15 8QH, UK; kit.macleod@hutton.ac.uk (C.J.A.M.); mads.troldborg@hutton.ac.uk (M.T.)
[3] Global Water Partnership, PO Box 24177, SE-104 51, Stockholm, Sweden; laurentcharles.tremblaylevesque@gwp.org (L.C.T.L)
[4] Sociology of Development and Change Group, Wageningen University & Research, P.O. Box 8130 6700 EW Wageningen, Netherlands
[5] Ministry of Water and Sanitation, Government of Malawi, Private Bag 390, Lilongwe, Malawi; modesta.banda@gmail.com M.K.))
* Correspondence: Rebekah.hinton@strath.ac.uk;

Abstract

Menstrual hygiene management (MHM) forms a critical component of ensuring access to adequate and equitable sanitation for all, as outlined in SDG6.2. Despite its importance, little is known about MHM in Malawi, particularly at a household level. Through a household survey of MHM within 2 districts, we evaluated the type of menstrual absorbents used by people who menstruate. Reusable cloths/rags were the most used menstrual absorbent, used by 79.5% of respondents, whilst disposable absorbents, such as tampons and sanitary pads, were used by 18.6% of respondents. Appropriate MHM also incorporates adequate management of MHM materials, including the washing and drying of reusable menstrual absorbents. We evaluated the cleaning of reusable menstrual absorbents; most respondents (90.1%) reported appropriate washing of menstrual absorbents using soap and water, however only 20.3% reported that menstrual absorbents were dried outside in the sun (as is best practise) with most reporting that reusable menstrual absorbents were dried inside their homes. Our findings highlight the need for improved MHM within Malawi, not only in the access and affordability of appropriate menstrual absorbents but also the promotion of appropriate washing and drying of menstrual absorbents.

Introduction

Menstrual hygiene management (MHM) has been defined by the WHO and UNICEF Joint Monitoring Programme as "Women and adolescent girls using a clean menstrual management material to absorb or collect menstrual blood, that can be changed in privacy as often as necessary for the duration of a menstrual period, using soap and water for washing the body as required, and having access to safe and convenient facilities to dispose of used menstrual management materials. They understand the basic facts linked to the menstrual cycle and how to manage it with dignity and without discomfort or fear"(UNICEF, 2019; WHO & UNICEF (JMP), 2012). Whilst ensuring appropriate MHM is not outlined as a specific goal within the SDGs, it is a central component of meeting the hygiene and sanitation needs of people who menstruate, thereby a central component of meeting sustainable development goal 6.2 "To achieve access to adequate and equitable sanitation and hygiene for all" (UN General Assembly). Furthermore, the importance of considering the 'needs of women and girls' in achieving equitable sanitation and hygiene is particularly emphasised in SDG6.2 (UN General Assembly). Moreover, appropriate MHM also strongly contributes to the achievement of other SDGs, namely, SGD3: "Good health and wellbeing", SDG4; "Inclusive and equitable quality education and promote lifelong learning opportunities for all"; SDG5: "gender equality and empower all women and girls"; and SDG8: "Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all" (Assembly, n.d.; Ssewanyana & Bitanihirwe, 2019).

Access to, and use of, appropriate menstrual absorbent materials is a critical part of ensuring appropriate MHM (Phillips-Howard et al., 2016). However, millions of people who menstruate in low- and middle-income countries still struggle to access appropriate MHM (Kambala et al., 2020). The most common menstrual absorbents used in resource-poor countries are "old cloths, tissue paper, cotton or wool pieces, or some combination of these items" (Kuhlmann et al., 2017, p 358). Reusable cloths are often made from bunching up and sewing scraps of old clothing, towels, or blankets (McMahon et al., 2011). In Malawi, rags and cloths used as menstrual absorbents are then often looped with string tied around the waist and further held in place by underwear (Pillitteri, 2011) . A study of schoolgirls in rural Uganda identified that 87% were using rags as menstrual absorbents (Boosey et al., 2014) whilst similar studies in Nigeria estimated that 31% and 55.7% of schoolgirls used toilet tissue or cloth as a menstrual absorbent (Adinma et al., 2008; Aniebue et al., 2009). When rags and cloths are unavailable, some people who menstruate must resort to using plant materials such as soft grasses (Boosey et al., 2014) and leaves (Vaughn, 2013) to provide a menstrual absorbent. In the absence of any appropriate menstrual absorbents, many people who menstruate are forced to isolate (Vaughn, 2013), this has particularly significant consequences for adolescents and has been linked to school absenteeism. One study in Uganda reported that over 60% of the girls surveyed reported missing school each month for menstrual-related reasons (Boosey et al., 2014). A similar study in Ethiopia found that girls who did not use menstrual absorbents were over five times more likely to miss school, some dropped out of school following teasing about blood-stained clothes. Furthermore, 58% of girls reported a decline in school performance after the onset of menstruation (Tegegne & Sisay, 2014). This is a significant consideration in reaching SDG4, achieving “inclusive and equitable quality education”. Commercially available, disposable menstrual absorbents are frequently reported to provide higher absorbency (Foster & Montgomery, 2021; Kambala et al., 2020) and are often a preferred form of menstrual absorbent (Hennegan et al., 2016), particularly by younger users (Kambala et al., 2020). However, many people who menstruate in low-resource countries are unable to use this method due to cost (Boosey et al., 2014; Vaughn, 2013) and may resort to using unsafe materials in menstrual hygiene management (Kambala et al., 2020; Vaughn, 2013).

The 2021 JMP MICS report for Malawi found that 97.3% of women reported having access to appropriate materials for menstruation during their last menstruation with 68.5% of women reporting using reusable menstrual absorbents. Reusable absorbents were more commonly used in rural communities and among older women (NSO, 2021). However, to evaluate whether such reusable absorbent use is appropriate, it is also important to consider the method of cleaning and management of reusable absorbents. Poor menstrual hygiene practices, particularly when using reusable absorbent pads, have been associated with urogenital and reproductive tract infections (Das et al., 2015; House et al., 2012.; Torondel et al., 2018). The method of washing and sanitising reusable menstrual absorbents is a particularly important consideration in assessing menstrual hygiene and health (Mahajan, 2019; Narayan et al., 2001; Ssewanyana & Bitanihirwe, 2019). Reusable menstrual absorbents should be washed using clean water and soap, as well as dried in the sun in order to minimise microbial growth (Das et al., 2015; Torondel et al., 2018). Access to appropriate menstrual hygiene management may also have a significant impact on psychological wellbeing (Roxburgh et al., 2020). Negative feelings towards menstruation are commonly reported (Chandra-Mouli & Patel, 2017; Vaughn, 2013, Roxburgh et al., 2020; Enzler et al., 2018) including “embarrassment, shyness, anxiety, shame, and stigmatization” (Kambala et al., 2020). Inadequate access to appropriate menstrual absorbents furthers such negative emotions; leakages and signs of menstruation are reported as a major cause of embarrassment and stigma surrounding menstruation (Kambala et al., 2020; Vaughn, 2013, Roxburgh et al., 2020).

Effective MHM has significant consequences for the health, education, economic potential, and gender equality for people who menstruate (Ssewanyana & Bitanihirwe, 2019). However, despite its importance, MHM information in Malawi is limited with no specific information on MHM reported in Census, MIS, and DHS surveys (NMCP and ICF, 2018, NSO 2018, NSO and Macro International, 2016). Studies where MHM has been investigated in Malawi often focus on MHM in schools (Grant et al., 2013; Mchenga et al., 2020; Pillitteri, 2011.; Shah et al., 2023). Whilst MHM within school settings in an important area, it is also vital to also evaluate MHM in the wider community (Kambala et al., 2020).

This study evaluates the types of menstrual absorbents used by people who menstruate in two districts of Malawi, examining both the type of menstrual absorbents used and methods for washing and drying of absorbents. Through a 2019 survey of over 900 households, conducted by trained NGO workers, MHM at the household level is investigated. The study underscores the necessity for enhanced MHM in Malawi, focusing not just on ensuring access to and affordability of suitable menstrual absorbents, but also on advocating for proper washing and drying practices for these absorbents. Specifically, this research paper addresses the following research questions: (1) What are the most common methods of menstrual hygiene management by people who menstruate in Malawi? (2) How are reusable menstrual absorbents washed and dried?

Methods

Study location

Malawi is a low-income country in south-eastern Africa with a population of 19.9 million (World Bank, 2023a), this is rapidly growing with an annual population growth rate of 2.6% (World Bank, 2023b). 70.1% of the population live below the international poverty line of $2.15/ day (defined in 2017)(World Bank, 2023c), this makes purchasing sanitary products for appropriate MHM a challenge.

Surveys were conducted within 2 districts of Malawi, not disclosed for anonymity purposes, referred to as districts A and B. Districts A and B were selected as part of a wider sanitation and hygiene survey (Hinton et al., *in review*) of communities that had both undergone several Community Led Total Sanitation (CLTS) interventions and subsequently declared as open-defecation free. CLTS is a behaviour change programme focused primarily on ensuring sanitary provision and ending open defecation on a community level, emphasising the community wide and environmental health significance of sanitary provision (Cavill et al., 2015). However, CLTS can also be expanded to address MHM, creating a holistic view of multiple aspects of sanitation and hygiene and emphasising the community wide and environmental health consequences of appropriate MHM (Roose et al., 2015).

Survey methodology

Interviews of a total of 939 households were conducted in 2 districts of Malawi, district A and district B. Interviews were conducted as part of a wider survey on sanitation and hygiene provision (Hinton et al., *In review*). Households surveyed belonged to the service area of 10 selected Healthcare Centres (HCC), six in district A and four in district B. Households within these service areas were selected on a stratified random sampling basis, taking the same proportion of households surveyed within each community (approximately 10-20%). Surveys were conducted by trained staff members in Chichewa and English. The interviews were conducted by trained NGO workers, in collaboration with District and Area Environmental Health Officers, and District Water Development Officers in Chichewa. Data was collected using a mobile based forms which were checked and validated by a verifier. Some of the enumerators used paper forms before transferring the data onto the mobile form later.

Surveys were conducted between the 7th and 25th of July 2019. Trained staff visited households and asked for a member of the household to answer a variety of questions relating to sanitation and hygiene. Regarding MHM, household members were asked “Which type of materials are used by women in this household to collect/absorb menstrual blood?”. Respondents were able to list multiple materials/methods, including the option to say, "don't know/refuse to answer". Respondents that seemed too uncomfortable (e.g., being silent for a while, turning around, or diverting the topic to something else) were recoded as "don't know/refuse to answer". Those using disposable tissues, e.g., wet wipes, paper towels, or ‘Kleenex’ type of materials, were recorded as “toilet paper”. Respondents that reported using reusable cloths or rags were then asked about management of the menstrual absorbents, including the method for washing and drying from several options. Respondents, therefore, did not necessarily menstruate themselves but, where they could, provided a response regarding the MHM of people who menstruate in the household. Where this was either not relevant or the participant had insufficient information to answer the questions, there was an option for no response to be given. To better understand MHM practices and views within the communities, several focus groups were organised with women groups prior and in parallel to the household surveys. Quotes from respondents have been anonymized.

Informed verbal consent of study participants was obtained prior to their participation. Before proceeding with the questionnaire, the interviewers provided background information on the survey (e.g., objectives, anonymity, length of the interview, etc.) and specified that the respondent could decide to not respond or skip a question or stop the interview at any time. Interviewers introduced themselves, mentioning the name and the organisation for whom they worked as well as where they could be contacted in case the interviewee would have any further questions or concerns after the survey.

Data interpretation

Responses were restricted to within the sample window specified and duplicate responses were removed prior to analysis. The type of MHM was summarised, any response which listed a type of menstrual absorbent was summed to give an estimate for the total number of people who use a given menstrual absorbent product. Results of the survey for district A and B are summarised separately to establish if any major differences between the districts existed.

The number of households without access to appropriate menstrual absorbents was calculated as the sum of households listing toilet paper or leaves as the only menstrual absorbent reported for MHM. The number of households with ‘at risk’ MHM practises was calculated as the sum of the total number of households using reusable menstrual absorbents with inadequate washing practices (households that did not wash menstrual absorbents or washed menstrual absorbents without soap) and the estimated number of households that had appropriate washing practices but inadequate drying practices. The estimated number of households with inappropriate drying was calculated as the total number of households where menstrual absorbents were washed with soap and water multiplied by the percentage of households that dried menstrual absorbents inside.

Results

Menstrual absorbents used

District A surveyed 733 households whilst 206 households were surveyed in district B, 714 and 187 households provided an answer regarding the menstrual absorbents used in district A and B respectively. The type of menstrual absorbent used by households is summarised in Table 1, multiple answers could be provided. Reusable cloths or rags were listed as a menstrual absorbent used by 79.5% of households in which the participant provided an answer: 81.1% in district A and 73.3% in district B. Disposable menstrual absorbents, such as tampons and pads, were used by 18.6% of households that provided a response: 16.5% in district A and 26.7% in district B. District A also reported that 0.42% and 1.96% of households that reported a method of MHM used toilet paper and leaves respectively, no households reported using these methods in district B.

In most cases, only one type of menstrual absorbent was listed as being used by households. Of the 716 households that reported using reusable cloths or rags, 699 households (97.6%) reported this as their only menstrual absorbent: 97.4% in district A and 98.5% in district B. 152 of the 168 households (90.5%) that reported using disposable absorbents (tampons or pads) reported these as their only menstrual absorbent, 15 reported using these alongside reusable cloths or rags (8.93%), and 1 household reported using disposable absorbents alongside an unreported method (don’t know/refuse to answer.) A total of 17 (1.81%) households used toilet paper or leaves as menstrual absorbents. Of the 3 households that used toilet paper, 2 reported this as their only menstrual absorbent whilst 1 household reported using toilet paper as well as reusable cloths/rags. Similarly, of the 14 households that reported using leaves, 13 reported that this was the only type of menstrual absorbent used, whilst 1 reported using leaves alongside reusable cloths/ rags.

Table 1: Type of menstrual absorbents used by households in district A and B.

Menstrual product	Number of households in District A using product	Percentage of households in District A using product (%)	Number of households in District B using the product	Percentage of households in District B using product (%)
Reusable cloth or rags	579	81.1	137	73.3
Don’t know/refuse to answer	35	4.90	19	10.2
Toilet paper	3	0.42	0	0
Leaves	14	1.96	0	0
Disposable (tampons or pads)	118	16.5	50	26.7

Washing and drying of menstrual absorbents

The method of cleaning reusable menstrual hygiene products was also evaluated, the results are summarised in Table 2. Overall, 99.0% of households that used reusable cloths or rags in MHM reported that they were cleaned: 99.1% and 98.5% in district A and B respectively. Of those houses cleaning reusable cloths or rags, 90.1% used soap and water (89.0% and 91.1% in district A and B respectively), whilst 9.94% cleaned with water only (10.1% and 8.89% in district A and B respectively).

Overall, 79.7% of households cleaning reusable menstrual products dried the absorbents inside their home and 20.3% dried menstrual absorbents outside, in the open air. 552 households in district A and 128 in district B provided an answer about how reusable menstrual absorbents were dried. 444 (80.4%) and 98 (76.6%) households reported that they were dried inside whilst 108 (19.6%) and 30 (23.4%) households reported that the products were dried outside in the open air in district A and B respectively.

Table 2: Type of washing of reusable menstrual absorbents in district A and B.

Method of cleaning menstrual absorbent	Number of households in District A	Percentage of households in District A (%)	Number of households in District B	Percentage of households in District B (%)
Not washed	5	0.9	2	1.5
Washed with water only	58	10.1	12	8.89
Washed with soap and water	511	89.0	123	91.1

In total, 77 (10.8%) households that used reusable menstrual hygiene products (and reported on the method of cleaning) were inappropriately washing their reusable menstrual hygiene products, either by not washing menstrual absorbents or washing with water only.) 79.7% of households using and washing reusable menstrual absorbents reported drying the products inside their home; an estimated 505 households wash menstrual absorbents with water and soap before drying these inside. Collectively, 582 of the households using reusable cloths or rags report either washing or drying their menstrual absorbents inappropriately; only 18.1% of households using reusable cloths or rags practised appropriate washing and drying.

Discussion

A major focus in ensuring adequate and equitable sanitation and hygiene is considering the menstrual hygiene management (MHM) of people who menstruate. This is specifically highlighted in SDG6.2, which emphasises the importance of paying special attention to the needs of women, girls and those in vulnerable situations (UN General Assembly, 2015).

Within Malawi, reusable menstrual absorbents are commonly used for MHM; 68.5% of women report using reusable menstrual absorbents whilst 28.5% use non-reusable absorbents and 2.6% have other/no materials (NSO, 2021). Higher levels of reusable menstrual absorbent use are reported in rural areas, by older women, poorer households, and those with a lower level of education (NSO, 2021). To investigate the types of MHM practised in greater details, we evaluated the results of a survey of 939 households conducted across 2 districts in Malawi (Hinton et al., *in review*). These results provide a comparison to the estimations of menstrual absorbent use and provide additional information about the types of absorbent used. Furthermore, crucially, this work also evaluates the cleaning of reusable menstrual absorbents, which can greatly impact their safety.

We investigated MHM by asking what materials are 'used by women in the household to collect/absorb menstrual blood'. Reusable cloths or rags were the most common method, used by 79.5% of all households that listed a method of menstrual absorbent. This was similar across both the districts investigated: 81.1% of households in district A and 73.3% of households in district B. These findings report a slightly higher level than the 2021 JMP MICS survey (reported 68.5% reusable absorbent use), however, this is likely due to the surveyed communities being in more rural areas (NSO, 2021). These findings are also consistent with further literature, which reports that reusable menstrual cloths are the most common form of menstrual absorbent used in menstrual hygiene management in Malawi (Pillitteri, 2011), similarly to other low-resource countries (Kuhlmann et al., 2017; Tegegne & Sisay, 2014). Where reusable cloths and rags were used in MHM, they were usually the only method of menstrual absorbent used; reusable cloths and rags were the only menstrual absorbent used in 97.6% of households in which they were used.

Reusable menstrual absorbents made of cloths and rags are less absorbent than commercially available sanitary pads (Foster & Montgomery, 2021), this can prove ineffective in managing menstrual bleeding, sometimes resulting in blood stains on clothes that result in embarrassment, stigmatisation, anxiety, and shame (Kambala et al., 2020; McMahon et al., 2011). Poor absorbency and staining of clothes have been reported as a particular concern for those attending school, with accounts of people who menstruate dropping out of school due bullying around these issues (Tegegne & Sisay, 2014). The fear of ridicule has also been reported to decrease the confidence of people who menstruate in school settings (Vaughn, 2013). In addition, cultural considerations surrounding menstrual blood are an important factor in appropriate MHM. There is a particular concern among by people who menstruate in Malawi about menstrual blood not being seen for fear of menstrual blood being used in witchcraft (Pillitteri, 2011). Within Malawi, 12.7% 'of women age 15-49 years reporting menstruating in the last 12 months did not participate in social activities, school or work due to their last menstruation' (NSO, 2021). This further emphasises challenges resulting from menstrual absorbents with inadequate absorbency. In cases where people who menstruate have access to more discrete menstrual products, which cannot be seen under clothing, some cultural beliefs and practises associated with menstruation, such as being unable to be in the same environment as a boy or man, appear to be dying out (Kambala et al., 2020). There are some reusable menstrual products, made from cloth, that offer improved absorbency and protection to using strips of cloth and rags, these are either locally made or commercially available reusable pads (House et al., 2012.). This survey did not specify the type of reusable cloths or rags used as menstrual absorbents; it may be possible that some users utilise purpose-made reusable pads which may provide better absorbency than strips of cloths or rags. Further studies could investigate the different type of reusable cloth menstrual absorbents used in Malawi and how improved reusable menstrual absorbents can be promoted.

Disposable menstrual absorbents were the second most common method, used by 18.6% of all households (16.5% in district A and 26.7% in district B). Disposable menstrual absorbents have greater absorbency than cloths and rags (Foster & Montgomery, 2021) and are often a preferred method of MHM (Hennegan et al., 2016) with reports of young girls in particular preferring disposable menstrual pads (Kambala et al., 2020). However, affordability poses a major limitation to the wider use of disposable menstrual absorbents (Boosey et al., 2014; Kambala et al., 2020; Vaughn, 2013) and concerns have also been raised about enabling safe management of used disposable menstrual products (House et al., 2012.; Kambala et al., 2020). Furthermore, most adults who menstruate report preferring reusable cloths or rags as these are a traditional form of MHM (House et al., 2012; Kambala et al., 2020). Malawi implemented a tax exemption (formally, a 16.5% levy) on menstrual pads from the 1st of April 2022 (The Star, 2023), whilst this may help to improve access to disposable menstrual pads, the cost of sanitary pads is still high. In most cases where disposable menstrual absorbents were used, these were the only type of menstrual absorbent (90.5%), however, 8.93% of households using disposable menstrual absorbents reported using them alongside reusable cloths and rags. This may be due to the high cost of disposable menstrual absorbents, with reusable cloths and rags being used alongside disposable methods despite a preference for disposable products (Kambala et al., 2020). Financial barriers are not only due to the affordability of products, access to financial resources is also a barrier to appropriate MHM with men often not providing access to money to purchase menstrual hygiene products (McMahon et al., 2011; Shah et al., 2023). This was echoed by participants who emphasised that there is a taboo of asking male household members for money to buy menstrual hygiene products.

Appropriate disposal of menstrual absorbents in also a concern, particularly in the case of disposable menstrual absorbent use. There is a wide lack of appropriate disposal of menstrual waste worldwide with menstrual absorbents typically disposed of by burying, burning or depositing absorbents in garbage or toilets (Kaur et al., 2018). It is recommended that discarded sanitary products should be incinerated for appropriate disposal (Parthasarathy et al., 2022).

Appropriate disposal of menstrual absorbents is important for ensuring environmental and community level health due to inappropriate disposal resulting in contact with disease causing pathogens from menstrual products (Kaur et al., 2018; Parthasarathy et al., 2022). Within Malawi, household waste is commonly disposed of within pit-latrines (Hinton et al., 2023), presenting a potential concern for groundwater contamination from disposed menstrual absorbents.

District A also reported that a small number of households used toilet paper and leaves as menstrual absorbents (0.43 and 2.00% of households respectively). These methods were not reported in district B, likely due to the smaller sample size of surveyed households within district B. Leaves have been reported as a menstrual absorbent (House et al., 2012; Vaughn, 2013) but have unreliable levels of absorbency (Foster & Montgomery, 2021) and present a high risk of contamination as well as being difficult and uncomfortable to use (House et al., 2012). In total, 15 households (1.60%) reported using only leaves or toilet paper for MHM, these were classed as households with inadequate access to menstrual absorbents for the purpose of this study. Most households had access to, at least basic, menstrual absorbents.

With people who menstruate mostly using reusable cloths and rags for MHM, washing menstrual absorbents is critical in ensuring appropriate menstrual hygiene in Malawi. Das et al. (2015) (Das et al., 2015) found that women using reusable menstrual absorbents were twice as likely to report a urogenital infection than women using disposable menstrual absorbents, whilst this may have been influenced by other hygiene practises or socioeconomic factors, it highlights the impact of menstrual absorbents on reproductive health. The washing and drying of reusable menstrual absorbents have been identified as a critical consideration (Mahajan, 2019), adequate washing and drying is central to the prevention of microbial growth on the reusable absorbent which may otherwise result in infections (Das et al., 2015; Torondel et al., 2018). Washing reusable menstrual products with water and but not soap has been shown to be associated with more symptomatic urogenital infections (Das et al., 2015). For the purposes of this study, reusable menstrual absorbents must be washed with soap to be classed as adequate MHM, this is consistent with other literature (Hennegan et al., 2016; Ramaiya & Sood, 2020). 99.0% of households that used reusable cloths and rags cleaned the menstrual absorbent, 90.1% of those households used water and soap to clean the cloths whilst 9.94% used only water. Whilst most households reported the use of soap in cleaning menstrual absorbents, it is difficult to measure the actual levels of soap usage in washing as the survey relied on self-reporting. Social perception is an important consideration in self-reported behaviours and may result in an overestimation of such practises (Hennegan et al., 2016).

Drying is also an important practice in the management of menstrual absorbents. Drying in the sun is a method of minimising microbial growth on menstrual absorbents due to the microbiocidal effects of UV light (Bloomfield et al., 2011; Das et al., 2015; House et al., 2012.; Mahajan, 2019; Torondel et al., 2018). Overall, 79.7% of households using, and washing, reusable menstrual products dried the absorbents inside and 20.3% dried menstrual absorbents outside. Despite the benefits of drying menstrual absorbents under the sun, most households dried menstrual absorbents inside the house, this may be due to the stigma surrounding menstrual hygiene as drying menstrual absorbents in the sun may cause embarrassment due absorbents being more easily seen (Averbach et al., 2009; Kuhlmann et al., 2017). This is similar to MHM techniques in other countries within Sub-Saharan Africa; within Uganda, a survey of schoolgirls in rural Uganda found that 41.6% of users dried absorbents outside with 47.4% of users drying menstrual absorbents hidden inside (such as under beds) where drying is especially limited, raising concerns for infection risk (Hennegan et al., 2016). Cultural attitudes are essential in consideration of washing and drying practices, as one of the focus group participants shared: "is a taboo to dry MHM materials (clothes/rags) outside the house, they should be dried inside the house" (personal communication, 18/03/2019). This is particularly relevant considering cultural attitudes and stigma associated with menstruation in Malawi (Pillitteri, 2011). Our results suggest that the biggest barrier to the appropriate management of reusable menstrual absorbents was not access to materials (such as soap) but rather inappropriate drying, we suggest that this may be linked to the stigma surrounding MHM.

Overall, we estimate that 81.9% of households using reusable menstrual absorbents had inappropriate washing or drying methods, including households not washing menstrual absorbents, washing with only water, and/or drying menstrual absorbents inside. Nonetheless, some women in the community know about health risks associated to improper washing and drying of reusable materials. One of the focus group participants shared that "rags/clothes which women use as vaginal pads should be washed with soap and air dried outside the house so as to get rid odour and infection (sic)" (personal communication, 18/03/2019).

Whilst this study provided a large-scale evaluation of MHM across two districts in Malawi, and an indication of MHM practises and challenges, the study also has key limitations. Surveys were conducted of household members as part of a wider survey on sanitation, therefore, in some cases, a household member who did not menstruate provided a response on the method of MHM used by menstruating household members. To minimise this leading to false responses, there was an option for interviewees to provide no response or state that they did not know. Future work would benefit from specifying whether the interviewee menstruated themselves.

Spatial variation may be another critical consideration in evaluating MHM across Malawi. Whilst this survey found similar results in both district A and B, it only surveyed communities within 2 districts making it hard to draw national conclusions. There may be significant spatial variation between districts that is not represented in these results. Notably, there may be differences between the most common MHM in urban and rural contexts, with people living in urban areas often having greater access to sanitation (Rossouw & Ross, 2021), future work could provide a more comprehensive overview of MHM across Malawi, accounting for variation between rural and urban communities. This was mentioned by focus groups who highlighted geographical challenges to accessing commercial menstrual hygiene products with users closer to trade centres speaking of using single use products more frequently. Furthermore, the two districts identified for the survey presented here were evaluated due to previously being declared open defecation (Hinton et al., *in review*), it may be that the districts presented here are not representative of MHM across Malawi due to previous investment into gender-sensitive sanitation and hygiene programmes in the district to achieve SDG6.2.

Our study indicates that, despite improvements in MHM in Malawi and government measures to promote safe MHM, a large proportion of people who menstruate have inadequate access to menstrual absorbents and do not practise safe cleaning of these products. To further understanding of MHM in Malawi, future country-wide surveys including Censuses, DHS, and MIS surveys, conducted by the Government of Malawi and in collaboration with partner organisations, should include space for more information on MHM.

Conclusion

Through evaluating menstrual hygiene management (MHM) across two districts in Malawi and surveying over 900 households, we find that reusable cloths or rags are the most used menstrual absorbent product, used by 79.5% of households. 1.6% of households surveyed did not have access to any appropriate menstrual absorbents and instead reported using only toilet tissue or leaves.

Investigating the nature of washing and drying of reusable menstrual absorbents provided an indication of hygiene challenges of reusable products. Whilst, in most cases, these are appropriately cleaned with soap and water (90.1% of households), most households did not dry the menstrual absorbents outside in sunlight (only 20.3% of households dried menstrual absorbents outside) which can be important in preventing microbial growth. Overall, we estimate that, despite most households having access to at least a basic menstrual absorbent (reusable cloths/rags or a disposable absorbent), appropriate management is holding back adequate MHM. Approximately 81.9% of households did not implement appropriate washing or drying of menstrual absorbents. We suggest that the stigma associated with menstrual hygiene may be preventing appropriate MHM with important public health consequences, particularly around the prevention of urogenital infections. Education and behaviour change communications campaigns around appropriate usage should highlight the importance of appropriate MHM.

Further studies into MHM on a national level in Malawi will be essential to better understand the status of menstrual hygiene in Malawi; enabling Malawi to reach SDG6.2 access to adequate and equitable hygiene for all. Additionally, further studies should explore barriers to appropriate MHM practice within Malawi, investigating social, cultural, and economic challenges.

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Consent

Informed consent was obtained from all subjects involved in the study. All data collected was in line with the Government of Malawi ethics and was agreed with each participant.

Data availability

Confidential data were provided by the Government of Malawi and CARE. All data summarised is provided here. Additional data was obtained from publicly surveys including US Aid Demographic Health Surveys (DHS) Government of Malawi Census Data and US Aid Malaria Indicator Surveys (MIS).

Conflict of Interest

The authors have no competing interests to declare.

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6.4.1 Postface

This paper answered RQ3 ‘What are challenges to sanitation and hygiene provision in Malawi?’ by achieving SO10 and evaluating MHM within Malawi. The paper identified the challenge of inappropriate washing and drying of cloths and rags used as menstrual absorbents as a barrier to ensuring appropriate MHM and providing hygiene provision. The high level of menstrual absorbents being dried inside (rather than outside) is identified as a particular barrier to appropriate MHM. For progress to SDG6 to address the needs of women and girls a focus on the promotion of appropriate MHM will be necessary.

6.5 Conclusion to this chapter

The chapter answered RQ3 ‘What are challenges to sanitation and hygiene provision in Malawi?’ by providing a comprehensive exploration of Malawi’s progress to SDG6.2 (sanitation and hygiene), highlighting the importance of adopting a holistic approach to SDG6, recognising the interdependence of goals related to clean water, sanitation, and hygiene.

Specifically, the chapter addressed RQ3 achieving several specific objectives. The chapter achieved SO7 by exploring current provision of sanitation in Malawi, identifying a challenge of inadequate quality of sanitation infrastructure, both in a high percentage of sanitary provision being unimproved sanitary facilities (R. G. K. Hinton et al., 2023) and a with few sanitary facilities offering privacy and security. The chapter met SO8 by evaluating future sanitation provision and prospects for ending open defecation in Malawi. Significant challenges facing Malawi’s progress to SDG6.2 were identified, including the need for a step change in the rate of sanitation provision for Malawi’s sanitary development to keep pace with population growth. The chapter achieved SO9, exploring the sustainability in the provision of sanitary facilities, identifying the short-term focus of achieving an end to open defecation as a potential barrier to sanitation provision due to slippage in sanitation progress seen soon after communities achieve ODF status. The chapter highlighted the need to shift to higher quality sanitation to achieve sustainable and equitable progress to SDG6.2.

In addition, to answer RQ3, the necessity of improvements in the provision of hygiene was explored. The chapter achieved SO10, exploring the status of hygiene provision through both handwashing and MHM. The chapter highlighted the inherent challenge in that removing barriers to hygiene provision not only requires consideration of resources but also behaviour change including promoting hygiene practices in education. A focus on MHM underscored the necessity of addressing the specific needs of women, girls, and vulnerable communities in sanitation and hygiene initiatives, placing an emphasis on the importance of gender equality within SDG6 frameworks.

Considering these findings, the chapter called for concerted efforts to enhance sanitation and hygiene provision in Malawi, incorporating considerations for gender equality, environmental sustainability, and a focus on long-term perspectives. It underscored the imperative of prioritizing comprehensive strategies that address the multifaceted dimensions of SDG6 to ensure meaningful progress towards sustainable development and improved well-being within Malawi.

The chapter had a focus on community initiatives to change patterns in sanitation and hygiene, recognising the significance of communities as agents of change in progress to SDG6. This is not only a commonly proposed strategy to promote sanitation and hygiene, as exemplified in community-led total sanitation (CLTS), it also closely aligns with a core ethos of SGD6, namely SDG6.B which aims to 'support and strengthen local community participation in improving water and sanitation management'. CLTS offers just one example of community engagement in progress towards SDG6.

The next chapter further explores specific examples of how local level solutions can address multiple challenges in SDG6 but answering RQ4 'What are local solutions to Malawi's water and sanitation challenges?'. The chapter focuses on the role of local-level solutions in addressing multiple barriers to achieving SDG6 discussed within this thesis.

6.5.1 SDG6 targets explored in this chapter

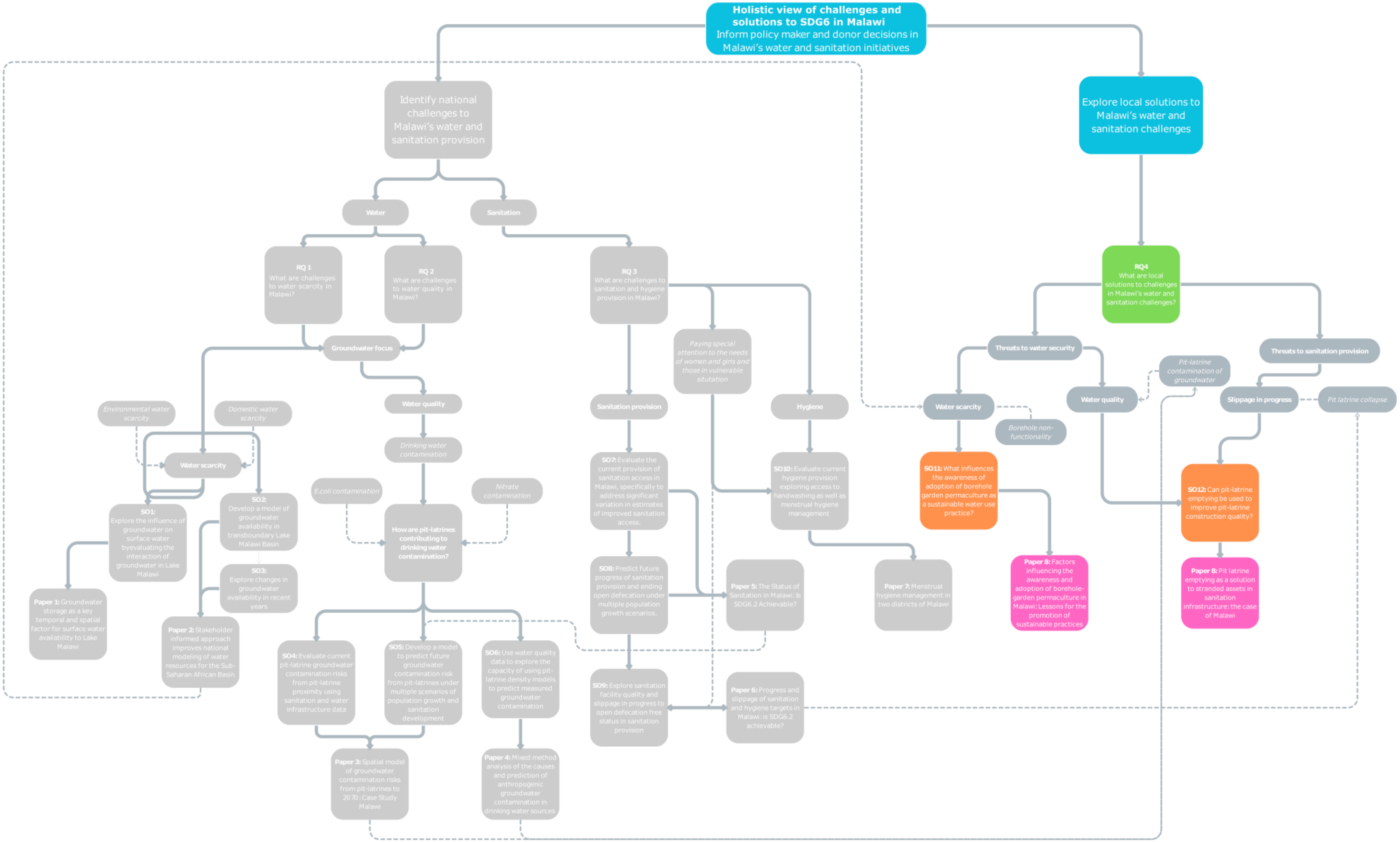
This chapter primarily addressed SDG6.2 ‘access to adequate and equitable sanitation and hygiene for all’. In addition, the chapter related to SDG6.3 ‘water quality and wastewater’ through discussion on the consequences for water contamination from inappropriate sanitation. The chapter also addressed SDG6.a ‘expanding water and sanitation support to developing countries’ through consideration of the long-term sustainability of investments in sanitation and hygiene interventions. Finally, the focus on CLTS as a method to promote sanitation and hygiene connected to SDG6.b ‘community participation’. These are shown in Figure 6.1.

Figure 6.1: SDG6 targets addressed in this chapter. This work primarily focuses on SDG6.2 ‘sanitation and hygiene and end open defecation’.

Chapter 7: Local level solutions to Malawi's Water and Sanitation Challenges

"It is not unreasonable that we grapple with problems. But there are tens of thousands of years in the future. Our responsibility is to do what we can, learn what we can, improve the solutions, and pass them on".

Richard Feynman, 1988


Holistic view of challenges and solutions to SDG6 in Malawi
Inform policy maker and donor decisions in Malawi's water and sanitation initiatives
Identify national challenges to Malawi's water and sanitation provision
Explore local solutions to Malawi's water and sanitation challenges
Water
Sanitation
RQ 1 What are challenges to water scarcity in Malawi?
RQ 2 What are challenges to water quality in Malawi?
RQ 3 What are challenges to sanitation and hygiene provision in Malawi?
RQ4 What are local solutions to challenges in Malawi's water and sanitation challenges?
Groundwater focus
Environmental water scarcity
Domestic water scarcity
Water scarcity
Water quality
Drinking water contamination
E.coli contamination
Nitrate contamination
How are pit-latrines contributing to drinking water contamination?
SO1: Explore the influence of groundwater on surface water byevaluating the interaction of groundwater in Lake Malawi
SO2: Develop a model of groundwater availability in transboundary Lake Malawi Basin
SO3: Explore changes in groundwater availability in recent years
Paper 1: Groundwater storage as a key temporal and spatial factor for surface water availability to Lake Malawi
Paper 2: Stakeholder informed approach improves national modeling of water resources for the Sub-Saharan African Basin
SO4: Evaluate current pit-latrine groundwater contamination risks from pit-latrine proximity using sanitation and water infrastructure data
SO5: Develop a model to predict future groundwater contamination risk from pit-latrines under multiple scenarios of population growth and sanitation development
SO6: Use water quality data to explore the capacity of using pit-latrine density models to predict measured groundwater contamination
Paper 3: Spatial model of groundwater contamination risks from pit-latrines to 2070: Case Study Malawi
Paper 4: Mixed method analysis of the causes and prediction of anthropogenic groundwater contamination in drinking water sources
Paying special attention to the needs of women and girls and those in vulnerable situtation
Sanitation provision
Hygiene
SO7: Evaluate the current provision of sanitation access in Malawi, specifically to address significant variation in estimates of improved sanitation access.
SO8: Predict future progress of sanitation provision and ending open defecation under multiple population growth scenarios.
SO9: Explore sanitation facility quality and slippage in progress to open defecation free status in sanitation provision
SO10: Evaluate current hygiene provision exploring access to handwashing as well as menstrual hygiene management
Paper 5: The Status of Sanitation in Malawi: Is SDG6.2 Achievable?
Paper 6: Progress and slippage of sanitation and hygiene targets in Malawi: is SDG6.2 achievable?
Paper 7: Menstrual hygiene management in two districts of Malawi
Threats to water security
Threats to sanitation provision
Water scarcity
Borehole non-functionality
Water quality
Pit-latrine contamination of groundwater
Slippage in progress
Pit latrine collapse
SO11: What influences the awareness of adoption of borehole garden permaculture as a sustainable water use practice?
SO12: Can pit-latrine emptying be used to improve pit-latrine construction quality?
Paper 8: Factors influencing the awareness and adoption of borehole-garden permaculture in Malawi: Lessons for the promotion of sustainable practices
Paper 8: Pit latrine emptying as a solution to stranded assets in sanitation infrastructure: the case of Malawi

Chapter 7: Local level solutions to Malawi's Water and Sanitation Challenges

7.1 Introduction

Chapters 4, 5, and 6 have identified a myriad of challenges hindering Malawi's progress towards achieving 'clean water and sanitation for all' as set out in SDG6 (UN General Assembly, 2015). Whilst these have explored some key policy recommendations and suggestions, they have typically identified *challenges* to SDG6 in Malawi, primarily considering these on a national scale. This chapter considers *solutions* in reaching SDG6, focusing on the local scale. The focus on the local scale addresses one of the core components of SDG6 is SDG6.B "support and strengthen local community participation in improving water and sanitation management" (UN General Assembly, 2015). In doing so the chapter recognises that involving communities in developing and implementing solutions in water and sanitation is paramount to meeting SDG6.

This chapter answers RQ4 'What are local solutions to Malawi's water and sanitation challenges?' by exploring two examples; borehole-garden permaculture (SO11) and pit-latrine emptying (SO12). These case-studies not only provide examples of local level participation in water and sanitation management, but also explore two examples of solutions to the multifaceted challenges explored within this thesis. The first case-study of borehole-garden permaculture primarily focuses on the challenge of water quantity, explored within Chapter 4, by evaluating the adoption of a sustainable water use programme. The second case-study, pit-latrine emptying, focuses on the joint issues of water contamination from pit-latrines, discussed in Chapter 5, and frequent pit-latrine replacement resulting in slippage in progress to ending open defecation, as discussed in Chapter 6, through a system of high-quality latrine construction coupled with pit-latrine emptying. Both case-studies epitomise the oft-touted phrase 'think globally, act locally' which emphasises the power of local level action to tackle large-scale challenges (Gerlach, 1991). The chapter responds to RQ4 through the specific objectives:

SO11: What influences the awareness of adoption of borehole garden permaculture as a sustainable water use practice?

SO12: Can pit-latrine emptying be used to improve pit-latrine construction quality?

This chapter is composed of two papers, published, or submitted, in international peer-reviewed journals, these are listed below:

Paper 8

Hinton, R. G. K., Macleod, C. J. A., Troldborg, M., Wanangwa, G., Kanjaye, M., Mbalame, E., Mleta, P., Harawa, K., Kumwenda, S. & Kalin, R. M., (2021) Factors influencing the awareness and adoption of borehole-garden permaculture in Malawi: lessons for the promotion of sustainable practices. *Sustainability*. 13, 21, 25 p., 12196**.**

Author contribution:

Conceptualization (R.G.K.H, C.J.A.M, M.T., R.M.K) data curation (R.M.K., G.W., M.K., E.M., P.M., K.H., S.K), formal analysis (R.G.K.H,), investigation (R.G.K.H, C.J.A.M, M.T., R.M.K., G.W., M.K., E.M., P.M., K.H., S.K), methodology (R.G.K.H., C.J.A.M., M.T., R.M.K.), validation (R.M.K., G.W., M.K., E.M., P.M., K.H., S.K), visualization (R.G.K.H), project administration (R.M.K), supervision (R.M.K, C.J.A.M, M.T), writing original draft (R.G.K.H), review and editing (R.G.K.H, C.J.A.M, M.T., R.M.K.)

Paper 9

Hinton, R. G. K., M., Kanjaye, Macleod, C. J. A., Troldborg, M. B. & Kalin, R. M. (*In review*). Evaluation of pit-latrine emptying practices as a solution to poor pit-latrine construction quality: the case of Malawi. *Hygiene and Environmental Health Advances*

Author contribution:

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

7.2 Factors Influencing the Awareness and Adoption of Borehole-Garden Permaculture in Malawi: Lessons for the Promotion of Sustainable Practices

Hinton, R.G.K. [1,2]; Macleod, C.J.A. [2]; Troldborg, M. [2]; Wanangwa, G.[3,4]; Kanjaye, M[3].; Mbalame, E [5].; Mleta, P [5].; Harawa, K[6].; Kumwenda, S [6,7].; Kalin, RM[1].

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1 Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow Gl lXJ, UK; robert.kalin@strath.ac.uk
2 The James Hutton Institute, Craigiebuckler, Aberdeen AB15 SQH, UK; kit.macleod@hutton.ac.uk (C.J.A.M.); mads.troldborg@hutton.ac.uk (M.T.)
3 Department of Water Resources, Ministry of Forestry and Natural Resources, Government of Malawi, Private Bag 390, Lilongwe, Malawi; gjwanangwa@gmail.com (G.W.); modesta.banda@gmail.com (M.K.); princemleta@gmail.com (P.M.)
4 Department of Earth Sciences, Environmental and Water Sciences, University of the Western Cape, Private Bag X17, Bellville 7535, South Africa
5 Department of Water Supply, Government of Malawi, Private Bag 390, Lilongwe, Malawi; emmambalame5@gmail.com
6 Water for People, Blantyre P.O. Box 1207, Malawi; kharawa@waterforpeople.org (K.H.); smkumwenda@yahoo.co.uk (S.K.)
7 BASEflow, Galaxy House, Blantyre P.O. Box 30467, Malawi Correspondence: rebekah.hinton@strath.ac.uk

Abstract: Using wastewater accumulating around rural waterpoints to irrigate community gardens, borehole-garden permaculture (BGP) presents a method of sustainable water management. BGP also presents public health benefits through the removal of stagnant water around boreholes, key Malaria breeding grounds, and through providing year-round food to supplement diets. By analysing a dataset of over 100,000 cases, this research examines the awareness and adoption of BGP across Malawi. Generalised linear models identified significant variables influencing BGP awareness and uptake revealing that socioeconomic, biophysical and waterpoint-specific variables influenced both the awareness and adoption of BGP. BGP had low uptake in Malawi with only 2.4% of communities surveyed practising BGP while 43.0% of communities were aware of BGP. Communities in areas with unreliable rainfall and high malaria susceptibility had low BGP awareness despite BGP being particularly beneficial to these communities. This work suggests that future work in the promotion of BGP should focus their efforts within these areas. Furthermore, this work highlights the value of community networks in knowledge sharing and suggests that such social capital could be further used by NGOs and the Government of Malawi in the promotion of BGP and other sustainable practices.

Keywords: permaculture; borehole management; sustainable practice; SDG6; Malawi; Africa; adoption; awareness; generalised linear model

1. Introduction

Malawi is a largely agro-based economy marked by subsistence, small-holder farming. Almost 80% of the population is reliant on rain-fed, small-holder agriculture [1]. Malawi is one of the poorest countries in the world with 50.7% of the population living below the poverty line and 25% living in extreme poverty [2]. Food insecurity is also prevalent; around 20% of the population are classed as undernourished [3]. The largely rain-fed nature of subsistence farming and limited resources of many farmers make Malawi's food supply particularly sensitive to water and climate stresses [1,2,4]. Climate change will worsen the fragility of agriculture in the region through an increased frequency and intensity of extreme weather events such as droughts and floods [5,6]. Pressure is further applied to natural resources and food security due to the growing population; Malawi is projected to have a five-fold population increase by 2100 [7]. Furthermore, plans for agricultural development in Malawi including the expansion of irrigation, will result in more water-stress in some regions [8]. Conservation and climate-smart agricultural technologies will be an important part of ensuring a sustainable future in Malawi's agricultural development [2,9-11], this has been acknowledged in country's own development plans [l]. To ensure maximal uptake of such practises, understanding how communities become aware of and adopt sustainable agricultural practises will be critical.

Over 100,000 water-points such as boreholes, hand-dug wells, and surface water provide the domestic water supply for around 65% of Malawi's population (82.3% of the rural population and 19.8% of the urban population respectively) [12]. Most of these water-points consist of boreholes fitted with hand pumps designed to provide water for up to 250 people. Many boreholes were originally constructed by the Government of Malawi (GoM); however, since the 1990s, non-governmental organisations (NGOs) and the private sector have massively increased the number of boreholes. Boreholes provide improved water provision as they are not reliant on rainfall and river flow which can be unreliable; however, unsustainable water use is currently leading to the depletion and degradation of groundwater in Malawi [13-15]. Unsustainable water use in Malawi is anticipated to increase with population growth and an increasingly commercialised agricultural system implementing large-scale irrigation [12]. Encouraging patterns of sustainable water management and will be essential for Malawi in achieving sustainable development goal 6 (SDG6): clean water and sanitation [16]. Furthermore, ensuring sustainable agricultural practices that promote sustainable water management strategies will be key to ensuring Malawi will meet sustainable development goal 2 (SDG2): zero hunger [17]. Borehole-garden permaculture (BGP) presents one example of sustainable water management. Excess water around boreholes accumulates as a result of rainfall, water spilt during borehole use, and some users using the borehole as a washing point [18]. Many boreholes are fitted with concrete 'aprons' at the base of boreholes alongside a soakway used to channel runoff water away from the waterpoint [19]. BGP proposes a method of borehole management in which excess water accumulating around boreholes is channeled into community-managed gardens (typically at the end of the soakway), providing a low-cost and sustainable method of irrigation for community gardens [20,21]. Effective BGP gardens can provide year-round food to supplement diets and have therefore been proposed as a method of increasing food security. Training, resourcing, and promotion of BGP is provided by a variety of stakeholders including NGOs and the GoM [20,22,23]. Alongside the benefits of sustainable water use and increased food security and nutrition, BGP presents public health benefits through removal of stagnant water which act as key breeding grounds for the malaria transmitting *Anopheles* mosquitoes and other water-borne diseases such as bilharzia [24]. Rivett (2018) [20] also proposed that funds generated from BGP could supplement the costs of borehole maintenance in Malawi. Work to expand the scope of sustainable agricultural and water management techniques, such as BGP, in Malawi has been carried out for more than 30 years [20,22,23]. However, despite the many advantages of the practice, this study found that uptake of BGP around Malawi has remained low with only 2.4% of water-points across Malawi adopting BGP.

Malawi's agricultural development plan involves the formation of cooperatives by small-holder farmers; small-holder cooperatives would enable access to increased financing to adopt technologies [25]. As a largely community-led practice, understanding the uptake of BGP should elucidate some of the complex nature of community adoption of agricultural techniques [26-29]. Understanding decisions made by group co-option of sustainable agricultural practises may further illuminate how best to target messaging regarding climate-smart agriculture to newly formed small-holder cooperatives. The lessons learnt relating to how a community adopts BGP may become evermore important in the changing landscape of Malawi's agricultural sector. This study aimed to enhance the understanding of BGP in Malawi through focusing on the research questions: (1) What is the extent of BGP awareness and adoption in Malawi? (2) Do the analysed variables influence BGP awareness and adoption? (3) What lessons for the future promotion of BGP can be learnt from where communities are aware of or adopt BGP? A dataset of over 100,000 water-points from across Malawi was analysed to identify the scope of BGP awareness and adoption. Evaluating socioeconomic, biophysical, and waterpoint specific factors through generalised linear model construction enabled this study to identify the key driving factors in BGP awareness and adoption.

2. Materials and Methods

2.1. Research Context

Malawi is a landlocked country in Sub-Saharan Africa, Figure 1. The current population of 19 million people is projected to have undergone a five-fold increase this century [7]. As a largely agrarian state, agriculture contributes around 21% of the country's gross domestic product (GDP) [30] and 75% of its exports [31]. Rain-fed agriculture is prominent, and most of the population (almost 80%) are reliant on rain-fed small-holder agriculture [l]. However, such reliance on rain-fed agriculture makes Malawi's food supply vulnerable to climatic events; the combined effects of devastating floods in 2014-2015 and dry periods in 2015-2016 resulted in agricultural drought, this is estimated to have left over 6.7 million people food-insecure [32]. Furthermore, Malawi loses an average of 1.7% of its GDP each year to losses resulting from droughts and flooding [33]. Malawi's vision of becoming an inclusive and self-reliant nation [1] recognises the need for developing a more reliable and resilient food system, this includes proposing the expansion of irrigation to provide a reliable water supply. Malawi has seemingly rich water resources due to the presence of lake Malawi and a network of rivers. However, Malawi's water resources will be put under increasing pressure due to climate change, projected population growth, and the intensification of agriculture including the expansion of irrigation [5-8,34]. Changes in land use, such as deforestation, largely influenced by agricultural development, will further place pressure on water resources [1,34-37].

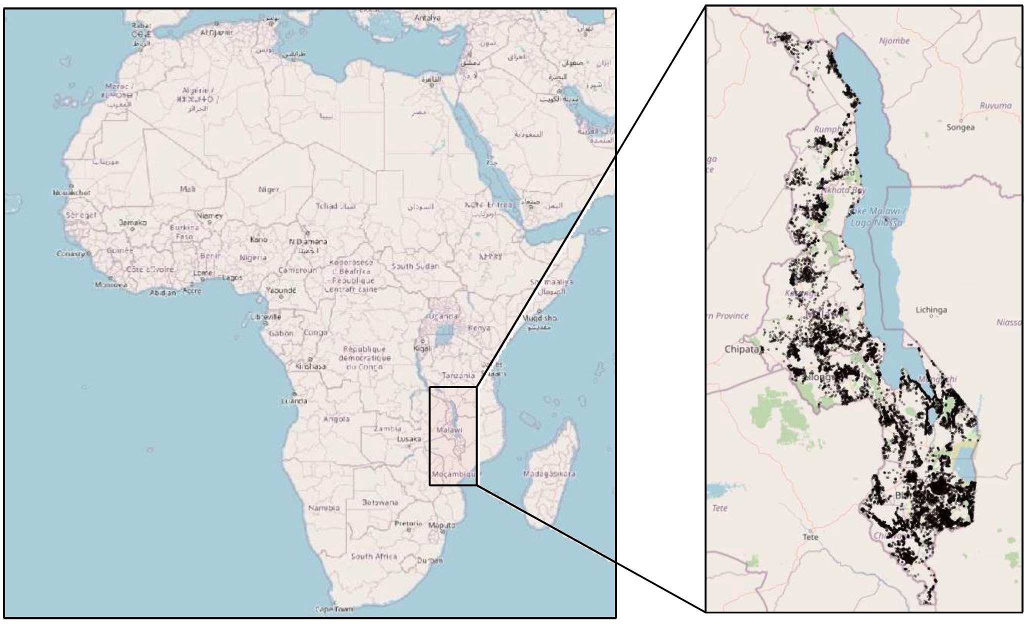

Figure 1: Map of Malawi with the point locations of water-points analysed in this study.

2.2 Waterpoint Survey

Data from over 100,000 water-points across Malawi, regarding the status of each rural waterpoint, was collected by the GoM through the Climate Justice Fund (CJF) between 2012-2021 [13,14,38,39]. Rural water-points around Malawi were systematically visited by trained GoM staff members who conducted questionnaire-based site inspections of the waterpoint and surveyed community members involved its management. Surveys were conducted in either English or Chichewa and the surveyors received training in survey conduction prior to the data collection. Data were quality-controlled at the University of Strathclyde. The data are accessed via a Management Information System (MIS) on the platform mWater [39,40]. A mixed-methods approach, qualitative and quantitative, was adopted to analyse the data [41].

The Malawian waterpoint survey provided qualitative survey data regarding how communities heard of BGP and, if rejected, why they rejected the practise [13]. Communities that reported they were aware of BGP but were not practising the technique were asked why they were not practising the technique. This was collated to identify some of the major reasons for the rejection of BGP. We identified the perceived barriers to the adoption of the practise.

2.3 Variable Selection

To inform the selection of variables, an exploration of literature evaluating variables influencing adoption of sustainable agricultural practices was conducted. Both 'social' and 'natural' variables were considered [42]. Biophysical constraints on the adoption of a sustainable practice are important for adoption [43,44]; however, social networks and social capital are also important [26-29,42]. Tey et al. 2013 [45] produced literature review of variables influencing the adoption of sustainable agricultural practices in Sub-Saharan Africa, these were classified into 6 major categories: socioeconomic, agroecological, institutional, information, perceived attributes, and psychology. Information regarding the perceived attributes of BGP, the psychology, information available, and institutional ties of the adopters were unavailable and beyond the scope of this research. Therefore, this research focused on variables classified as socioeconomic and biophysical (or agroecologi- cal) variables. Biophysical variables were identified as variables relating to the physical location of the waterpoint including climatic factors, biological factors, and connectivity to resources such as markets or other communities. Furthermore, variables relating to the wa- terpoint itself and waterpoint management were analysed based on literature highlighting the significance of the waterpoint committee in BGP adoption [20]. We investigated the influence of neighbour adoption of sustainable agricultural techniques through calculating the distance from each waterpoint to the nearest BGP practising waterpoint. The variables selected for analysis are summarised in Table 1.

Table 1. Variables investigated for their influence on the adoption of BGP. Variables are grouped into

3 categories (Socioeconomic, biophysical, and waterpoint specific features).

Category	**Subcategory**	**Variable**
Socioeconomic	Education	Mother education
		Literacy
	Population	Population density
	Poverty	Average poverty level
	Healthcare	Healthcare infrastructure
	Female-headed household	Female-headed household index
Biophysical	Climate and water availability	Temperature trend Precipitation index
		Irrigation index
	Extreme weather events	Forest fires index
		Riverine flooding index
	Soil	Soil organic carbon index
	Malaria susceptibility	Malaria susceptibility index
	Connectivity	Market accessibility time
		Distance to closest BGP practicing water-point
Waterpoint specific features	Waterpoint committee (WPC)	Number of people on WPC
		Number of women on WPC
	Waterpoint users	Number of waterpoint users
		Maximum distance of users to waterpoint
	Waterpoint functionality	Number of months water is unavailable
	Maintenance and management	Preventative maintenance performed
		Tarriff or user fee for the waterpoint

2.4 Variable Extraction

Initial cleaning of the dataset to remove incomplete or duplicate cases resulted in 75,013 boreholes for analysis. Variable data were collected from open-source data including datasets from the Regional Centre For Mapping Of Resources For Development (RCMRD) [46] and

SERVIR-Eastern and Southern Africa [47]. Data on the locations of districts and traditional authorities in Malawi was accessed from The Human Data Ex- change [48] and was provided by the Malawi National Statistical Office in 2018.

Data were accessed as a raster file and the variables at each individual waterpoint were extracted using a geographic data analysis and the modelling tool 'Raster' [49] using R Statistical Software (version 4.1.0) [50] in RStudio [51]. Further information regarding the sources for each variable, their definitions, and the values of the data is provided in the Appendix A Variables relating to the status of the specific waterpoint and management of the waterpoint were gathered from the waterpoint survey [13]. The distance between each individual waterpoint to the closest BGP practising waterpoint was calculated using information about the point locations of each waterpoint using Pythagorean theorem. The closest BGP practising waterpoint was identified though iterative calculation of the distances and updating the closest distance if a closer waterpoint was identified.

2.5 Generalised Linear Model Construction

The adoption of BGP was viewed as a two-stage process: awareness of BGP followed by the decision to adopt or reject the technique [44]. Variables influencing both stages were investigated through the construction of generalised linear models (GLMs) [52]. The use of a GLM enabled the relationship between the binary response variable and independent, continuous, and binary predictor variables to be analysed. The adoption (or knowledge) of BGP was modelled as a binary variable, 'yes' being the practise (or knowledge) of BGP and 'no' being where BGP was not practised (or heard of). The default variable is taken as 'No'. As both categorical and continuous variables were being used to model a binary response variable, a logistic regression model was used [53] The GLM function in base R [50], using RStudio [51,54] was applied to generate the models.

Forward-variable selection was used to generate a model providing the simplest possible explanation of the variables by iteratively adding predictor variables. The Bayesian Information

Criterion (BIC) value was calculated at each stage and the model with the lowest BIC value was selected, therefore selecting the model which could adequately explain the data with the fewest variables [55]. The method is less susceptible to collinearity than reverse variable selection models (although collinearity between variables was also calculated, Section 2.6), which was particularly important for the selection of variables here as many of the variables are interrelated.

The data were subsetted into a training and testing dataset [56] through the random allocation of 70% of the dataset being used to generate the model and testing the model with the remaining 30% of the data [57]. The training subset was used to generate a GLM, and the R 'Predict' function [58] was used to predict whether a given waterpoint would adopt (or be aware of) BGP based on variable values. The predicted outcome was compared to the testing subset of the dataset [59]. A confusion matrix was used to calculate the accuracy, sensitivity (true positive rate), and specificity (true negative rate) of the model. Models containing all variables (not generated through forward-variable selection) were generated for where communities were aware of or practising BGP to confirm that forward-variable selection did not result in the loss of predictive power (Appendix A Tables AS and A6). Repeating the process of forward-variable selection with different randomly generated training datasets resulted in the same variable selection.

Due to the low percentage of BGP adoption, an imbalance classification problem was identified in the model where BGP was adopted in communities aware of BGP. The ROSE function [60] was used in RStudio to oversample the minority class in the training dataset. Oversampling was selected as a method of balancing the highly unbalanced dataset as it ensures that there is no information loss [61]. There were no changes made to the testing dataset.

2.6 GLM Assumptions

GLMs have several probabilistic assumptions: linearity, response distribution, independence, and multicolinearity. [59]. Assumptions were checked for both GLM models using the R functions lm [62] and the Variance Inflation Factor (VIF) [63]. All assumption plots are in the Appendix A.

Linearity between the transformed response variable and the predictor is a key assumption of GLM. The linearity assumption was checked using a residuals vs fitted values plot, this was to confirm that there was no significant trend in the residuals. The models met the assumption on response distribution through examining the approximate normality of the deviance residuals. A Q-Q plot was constructed to identify any deviance residuals that are significantly non-normal. The independence assumption was confirmed through the absence of autocorrelation in residuals. The lack of autocorrelation in residuals was identified through deviance residuals plots to confirm the absence of significant tracking of residuals. Finally, the assumption of a lack of multicolinearity was confirmed through the calculation of the VIF for each variable. The VIF value calculates the linear relations; a VIF value exceeding 5 suggests a problematic level of colinearity [64]. All VIF values calculated were below 3, confirming there was no problematic level of multicolinearity, Table Al.

3. Results

3.1. Extent of Borehole-Garden Permaculture Uptake and Spatial Variation

Overall, 43.0% of surveyed water-points in Malawi were aware of BGP (32,256). Of those water-points, 5.6% (1800) had adopted the practise; an overall adoption of 2.4% across all surveyed water-points in the cleaned dataset (75,013). A map of where BGP is practised highlights the spatial variation in BGP practise in Malawi with some regions showing a much greater percentage adoption than others, Figure 2.

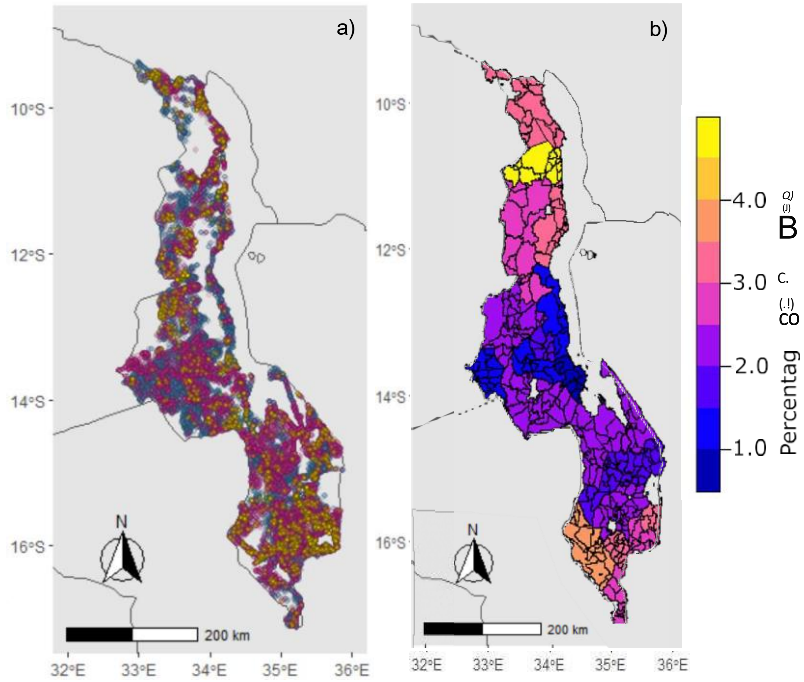

Figure 2. The distribution and percentage adoption of BGP in Malawi. (a) Depicts whether each waterpoint surveyed practised BGP (yellow), were aware of BGP but was not practising it (magenta) or had not heard of BGP (blue). (b) The percentage of water-points in a district which practise BGP. Traditional authority lines are shown too.

The district with the lowest BGP practise, Likoma, had 0.08% of water-points practising BGP, while the district with the highest percentage of BGP, Rumphi, had 4.5% of waterpoints practising BGP, Table 2. . A summary of the individual adoption percentages of each district is provided in the Appendix A.

Table 2: Percent of waterpoints in each district that adopted BGP.

District	Percentage of BGP Practice
Rumphi	4.53
Chikwawa	3.72
Mwanza	3.55
Chipita	3.25
Karonga	3.20
Nkhatabay	3.17
Phalombe	3.01
Thyolo	3.01
Nsanje	2.97
Mzimba	2.95
Mulanje	2.79
Blantyre	2.44
Ntcheu	2.42
Dedza	2.39
Chiradzulu	2.38
Kasungu	2.21
Lilongwe	2.16
Zomba	2.16
Mangochi	2.06
Ntchisi	1.86
Machinga	1.66
Balaka	1.63
Neno	1.60
Lilongwe	1.46
Dowa	1.44
Nkhotakota	1.38
Mchinji	1.28
Salima	0.09
Likoma	0.08

3.2 Variables Influencing Knowledge of BGP

Of BGP practising water-points that responded to the question 'How did you learn about permaculture?', 52.6% reported having heard about BGP from neighbours, 25.3% from the GoM, and 22.1% from an NGO, Figure 3. The locations of communities practising BGP and how they learnt about BGP were plotted to see if there were any significant differences in the spatial distribution of how communities had learnt of the practise. No noticeable clustering of how boreholes had come to learn about BGP was evident with the Malawian government, neighbours, and NGO capacity building about BGP widespread across Malawi.

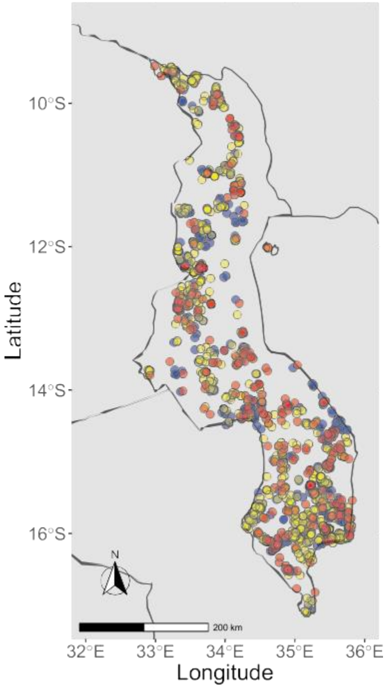

Figure 3. How communities practising BGP were aware of the technique represented spatially. Individual BGP practising water-points that were aware of BGP from the GoM are in red, neighbours are shown in yellow, and NGOs are shown in blue

The production of a forward-variable selection GLM enabled further investigation of variables contributing to where communities were aware of BGP, the results of the model are summarised in Table 3. The GLM correctly predicted whether 71.9% of communities were aware of BGP.

Table 3. GLM produced using forward-variable selection to explain variables influencing where communities are aware of BGP. Variable estimates alongside standard deviation (shown in brackets) are given. BIC Value: 39,500. AIC Value: 39,300. The model correctly predicted 71.9% of cases where BGP has been heard of (9219 correct predictions, 3603 incorrect predictions). Sensitivity 0.516, specificity 0.684). Significance codes: *** (0 < p :S: 0.001); ** (0.001 < p :S: 0.01); * (0.01 < p :S: 0.05). Non-significant results (p-value > 0.05) are marked with 'NS'.

Variable	**Variable Estimate (x0.001)**	**Significance**
Socioeconomic Variables		
Female-Headed Household	+16.3 ± 1.17	***
Mother education level	+4.21 ± 0.423	***
Population	-14.0 ± 4.90	**
Poverty	+11.1 ± 1.59	***
Biophysical Variables		
Irrigation	+9.59 ± 2.01	***
Malaria susceptibility	-11.9 ± 0.864	***
Market accessibility time	+2.1 ± 0.665	**
Precipitation trend	+6.94 ± 0.908	***
Riverine flooding	-12.4 ± 3.49	***
Soil Organic Carbon	-27.9 ± 3.24	***
Distance to a BGP practising water-point	-166 ± 10.6	***
Water-point (WP) specific Variables		
How many people usually use this WP	+0.0706 ± 0.0235	**
How many women are on the WPC?	-8.97 ± 7.42	NS
Maximum distance a user walks to WP	+0.112 ± 0.0264	***
Preventative maintenance performed	-133 ± 29.8	***
Tariff or user fee for the WP	+142 ± 35.8	***

3.3 Variables Influencing Adoption of Borehole-Garden Permaculture

The forward-variable selection GLM of where BGP was adopted in communities that were aware of BGP using a balanced dataset correctly predicted 61.4% of where BGP was adopted. The results of the GLM model are summarised in Table 4.

3.4 Reasons for Rejection of Borehole-Garden Permaculture

The reasons given for why communities that were aware of BGP did not adopt the practise are summarised in Table 5. The most common reason was a lack of common land at the end of the soakway, this included both no land and owners of the land disallowing BGP.

The fourth most commonly listed reason for why BGP was not practised was due to non-functionality of the waterpoint or limited water. The functionality of surveyed water- points is shown in Table 6. Functionality is a temporally sensitive variable and represents only a 'snap-shot' of functionality at a given point in time [38,65], the classification of 'partially functional' alongside 'functional' and 'nonfunctional' water-points enables a clearer depiction of waterpoint functionality over time.

Table 4. GLM using forward-variable selection to explain variables influencing where BGP is practised in places where it has been heard of. BIC value: 1920 AIC value: 1840. Correctly predicted the status of which boreholes adopted BGP in 61.4% of cases (3440 correct and 2165 false predictions). Sensitivity 0.551, specificity 0.617. A sample dataset an equal number of water-points that adopted and rejected BGP was analysed, a ratio of 70:30 was used for the data used for training:testing. Significance codes: *** (0 < p ::,;0.001); ** (0.001< p ::,;0.01); * (0.01 < p ::,;0.05).

Variable	**Variable Estimate** (x **0.001)**	**Significance**
Socioeconomic Variables		
Healthcare infrastructure	+4.08 ± 1.14	***
Mother education level	+3.80 ± 4.63	***
Female-headed household	-8.01 ± 1.08	***
Poverty	+9.11 ± 2.22	***
Biophysical Variables		
Precipitation trend	+21.1 ± 0.984	***
Soil organic carbon	+45.2 ± 4.00	***
Riverine flood index	-76.2 ± 12.9	***
Market accessibility time	+3.80 ± 0.716	***
Temperature trend	+8.57 ± 1.86	***
Irrigation	+11.8 ± 2.51	***
Waterpoint (WP) specific Variables		
Number of months water is not available	-120 ± 1.10	***
Number of women on the WPC	+104 ± 7.84	***
Maximum distance a user walks to the WP	+0.336 ± 0.0274	***

Table 5. The most common reasons given by communities that were aware of BGP but were not practising the technique for why they were not practising BGP.

Reason for BGP Rejection	Incidence	Percentage
No common land at end of soakway /not allowed	13,000	42.2
Not interested	7070	23.0
Lack of knowledge/ awareness/no community training	4310	14.0
Limited water/nonfunctional waterpoint	2380	7.74
Limited money	981	3.19
No access to seeds	712	2.31
Yet to start/temporary pause	649	2.11
Animals (eat crops or drink surplus water)	497	1.61
Salty water /poor water quality	457	1.48

Table 6. Functional status given of water-points surveyed. Functional: a waterpoint that provides year-round water. Partially functional: a waterpoint that provides water but is not reliable. Nonfunctional/No longer exists or abandoned: water-points do not provide any water.

Waterpoint Functionality	Incidence	Percentage
Functional	45,300	61.3
Partially functional but in need of repair	15100	20.4
Not functional	8410	11.4
No longer exists or abandoned	5100	6.9

Table 7. Summary of the results of analysed variables on BGP knowledge and adoption in a the minimal-variable GLMs in which variables were selected by positive variable selection. (+) denotes a significant positive variable estimate, (-) denotes a significant negative variable estimate and 'NS' (not significant) is written for any variable estimate with a p-value of >0.05.

Variable	**BGP Awareness**	**BGP Adoption**
Socioeconomic Variables		
Female-headed household	+	
Healthcare infrastructure		+
Mother education level	+	+
Population density		
Poverty	+	+
Biophysical Variables		
Irrigation	+	+
Malaria susceptibility		
Precipitation trend	+	+
Riverine flooding		
Soil organic carbon Market		+
accessibility time	+	+
Distance to BGP practising waterpoint		
Temperature trend		+
Waterpoint (WP) specific variables		
Maximum distance a user walks to the WP	+	+
Number of months water is unavailable		
Number of users of the WP	+	
Number of women on the WPC	NS	+
Preventative maintenance performed		
Tariff or user fee for the WP	+	

4. Discussion

The variables influencing the awareness and adoption of sustainable agricultural techniques are complex [10,11,45,66-71]. BGP implementation requires decisions through community management and engagement. The adoption of BGP, and other sustainable agricultural techniques, is dependent on communities being aware of BGP and choosing to adopt the practise [10,44]. Both stages are influenced by a range of factors including socioeconomic, biophysical, and waterpoint specific variables [20,42,43]. Investigating the processes of communities becoming aware of BGP and adoption of the practise as individual steps, with unique variables influencing them, can help to elucidate areas of focus for policy and practise.

4.1. Limitations

Although this research analysed a range of variables including socioeconomic, bio- physical, and waterpoint specific variables, this study did not analyse all the variables which influence this process, and it does not aim to provide a conclusive description of all variables involved. The socioeconomic variables analysed were a measure of the average level of the specific socioeconomic variable at a given location. Although this aimed to provide information on the average status of the community (i.e., poverty level), this may not be a true reflection of the status of the community as a whole. In the case of poverty, the average poverty level in a region may not sufficiently explain the availability of financing to a given community. This study revealed the large spatial heterogeneity of BGP adoption, while this may reflect the socioeconomic, biophysical, and waterpoint specific variables explored in this study, there are also significant regional differences. Many of these differences centre around traditional authorities and may reflect the differences culture and ethnography between regions. Although this study does explore some of the reasons why communities did not adopt BGP, further qualitative data would be beneficial to further explore the reasons behind BGP adoption and rejection.

4.2 Summary of Variables Influencing BGP Awareness

The knowledge of BGP is influenced by a range of variables including socioeconomic and biophysical variables as well as waterpoint specific considerations [10,42]. Population density was found to be an important variable, communities in areas with lower population densities (rural areas) were more likely to be aware of BGP, Table 7. The rural nature of BGP practise may also explain some of the other variables found to be significant in where communities were aware of BGP including poverty levels and the proportion of female- headed households, both of which are higher in rural areas [72]. However, such trends may not be completely explained by differences in rural and urban areas. For example, NGOs may also focus work in poorer areas too therefore leading to a higher level of BGP knowledge in poorer areas.

Biophysical geographical variables were significantly linked to where communities were aware of BGP, Table 7. Increased water availability, both through irrigation and precipitation, resulted in an increased knowledge of BGP. Areas with higher levels of irrigation generally have a more established agricultural sector, it may be that they are more likely to have heard of sustainable agricultural practises such as BGP. Although in the case of irrigation this may be partially explained by population density, no significant relationship between precipitation and population was observed indicating that the link between precipitation and BGP awareness cannot be explained by population density.

However, although areas with unreliable rainfall were less likely to be aware of BGP, these are some of the areas where BGP could be most beneficial through providing reliable irrigation to the BGP garden and enabling year-round food production [20]. Sustainable water management will become more critical with projected increases in temperature and reductions in rainfall in Malawi due to climate change, particularly in areas already experiencing water scarcity [5,6]. Areas already experiencing unreliable precipitation should be key targets of sustainable water management techniques such as BGP. As well as areas with lower precipitation trends, areas with high malaria susceptibility would benefit from BGP as the removal of stagnant water around boreholes prevents mosquitoes breeding [24]. However, despite the evident benefits, areas with an increased malaria susceptibility were less likely to be aware of BGP. Furthermore, this trend cannot be explained by communities in rural areas being more aware of BGP as Malaria susceptibility is negatively correlated with population density. This trend also does not appear to be the result of BGP practises already implemented in the area as adoption rates of BGP are not high enough to significantly change the malaria susceptibility. The underlying reason for why areas with less reliable rainfall and higher malaria susceptibility were less to be aware of BGP is not entirely clear. It is likely that these reflect where NGOs and influential individuals have focused efforts in expanding the knowledge of BGP [23].

Communities in which users walked further to access the waterpoint reported higher awareness of BGP, this may be explained in that rural areas have more disparate users and therefore this reflects the higher awareness of BGP in rural areas. Water-points with more users also had higher BGP awareness, despite rural areas having fewer users; the importance of the number of users of a waterpoint in where communities had heard of BGP highlights the importance of community knowledge [26-29,73,74]. The importance of community knowledge and social capital in where communities were aware of BGP was further highlighted by the significant role that neighbours played in increasing knowledge of the practice; communities closer to other communities practising BGP were significantly more likely to have heard of the practice. Furthermore, awareness of BGP from neighbours was the most commonly cited reason for how communities became aware of the practice, Figure 3.

External inputs also had a significant effect on which communities were aware of BGP. Communities that pay a tariff or user fee for the waterpoint had higher levels of BGP awareness. This may indicate that communities with active management have more external input and are more likely to be aware of BGP. However, the opposite trend was observed for communities with water-points for which preventative maintenance is performed; where preventative maintenance was performed there was reduced awareness of BGP. This was a surprising result and understanding the dynaMICS for why this may be the case was beyond the scope of this study; however, it does suggest that providers of preventative borehole maintenance could be used more in promoting awareness of BGP in communities.

4.3. Summary of Variables Influencing Where BGP Is Adopted

Regarding where borehole-permaculture is most likely to be adopted if communities are aware of the practice, physical constraints are important [43,67]. Communities in areas with reliable rainfall (higher precipitation trend) were more likely to adopt the practice. Communities in areas with increased levels of irrigation were also more likely to adopt BGP, suggesting a similar trend to precipitation in that communities in areas with greater water availability are more likely to adopt BGP. It may be that areas with more reliable rainfall and increased irrigation have a more robust agricultural system and therefore may be more inclined to adopt new agricultural techniques. Alternatively, areas with lower water availability may have alternative water priorities. For example, 'animals' was given as a reason for the rejection of BGP in areas aware of it in almost 500 cases: this referred to either animals eating crops grown or excess water being used as drinking water for animals. When limited water is available, retaining pools of water around boreholes to use as drinking water for livestock may be a higher priority for communities than using the water for crops [20]. Rivett et al., 2018 [20] suggested that water quality/ salinity could be a constraint on BGP adoption as water salinity can prevent crop growth. Drier areas may have greater problems with salinity and therefore this may explain the reduced BGP adoption in areas with reduced precipitation trend [75]. The observed result that 457 water-points listed salinity or poor water quality as a reason for BGP rejection supports this. Although communities in areas with increased water availability showed greater adoption of BGP, communities at risk of riverine flooding were less likely to adopt BGP. This may become an evermore important consideration in encouraging the adoption of sustainable agricultural practices as climate change is likely to lead to an increased frequency of extreme weather events [5,6]. In the case of BGP adoption, the formation of a BGP garden requires investment of both time and finances. Communities at risk of riverine flooding may be less willing to invest the temporal and financial commitment required to develop a BGP garden if the garden is at risk of destruction by extreme weather events such as flooding. The temperature trend is another climatic variable that was significant in where BGP was adopted. Communities that were aware of BGP in areas with higher temperature trends were more likely to adopt BGP, the underlying reason for this trend is not understood. Soil fertility was another important consideration in BGP adoption, communities in areas with higher soil organic carbon were more likely to adopt BGP. It may be that areas with high soil organic carbon have a more robust agricultural sector and are more willing to adopt agricultural practises. Communities that had reduced access to markets were also more likely to adopt BGP. It may be that communities with reduced market accessibility have a greater requirement to grow their own food and therefore BGP gardens have a more significant role in supplementing diets.

Other physical constraints, such as the absence of common land at the end of the soakway, were highlighted from asking communities why they were not practising BGP, Table 5. This was often due to land around boreholes being owned by individuals rather than by the water-users association of waterpoint committee. Such physical constraints in land availability may partially explain some of the increased prevalence of BGP in more rural communities. Waterpoint functionality is also a significant physical constraint; communities with water-points where water is unavailable for some months of the year were less likely to adopt BGP. Furthermore, partial or non-functionality was the 4th most commonly listed reason for why BGP was not taken up by communities aware of BGP. 35.2% of the surveyed water-points reported some level of non-functionality, ensuring improved waterpoint functionality in Malawi will therefore also be important in expanding the adoption of BGP.

The presence of an established waterpoint committee was an important variable in where BGP was adopted, emphasising the importance of community organisations and co- ordination in natural resource management [76]. The number of women on the waterpoint committee was a significant variable in where BGP was adopted; waterpoint committees with more women were more likely to adopt the practice. Waterpoint committee guidance stipulates that at least 50% of the waterpoint committee members should be women. Committees following the waterpoint committee guidance regarding female representation may be more likely to adopt other good practices in waterpoint management such as BGP. The maximum distance a user walks to collect water from a waterpoint was a statistically significant variable too, communities with more dispersed users appeared more likely to adopt BGP. It is not clear why this would be the case;

however, the distance users walk is strongly correlated with both population density and the number of people who use the waterpoint.

Socioeconomic factors were also significant in where BGP was adopted in communities that were aware of BGP. The development of a BGP garden requires financial investment, limited money and no access to seeds were both cited as reasons for why communities that had heard of BGP did not adopt the practice, Table 5. Therefore, it was surprising that communities in areas with higher poverty levels were more likely to adopt BGP. It may be that communities in areas with high poverty levels are more reliant on initiatives such as BGP gardens to supplement diets and provide an additional source of income. Areas with higher levels of mother education had higher levels of BGP adoption highlighting the important role of women in BGP adoption. Female-headed household index was also an important variable in where BGP was adopted, communities in areas with higher proportions of female-headed households were less likely to adopt BGP. This may reflect the largely male-dominated nature of land holding and ownership in Malawi [77] in which the capacity for women to adopt BGP is restricted by land ownership, this would be an insightful area for further study. Healthcare infrastructure was another significant variable in where BGP was adopted, areas with more healthcare infrastructure had higher levels of BGP adoption. It is not entirely clear why this would be the case, however, as BGP has important public health benefits it may be that communities in areas with increased healthcare infrastructure will receive more encouragement to adopt practises which lead to the removal of stagnant water, such as BGP.

4.4. Key Lessons for Government and NGOs

BGP presents an effective technique for ensuring sustainable water use and is particularly beneficial as a method of sustainable irrigation in areas with unreliable rainfall. The removal of stagnant water from boreholes furthermore presents an important public health benefit through the removal of mosquito breeding grounds [24]. However, despite the evident benefits to communities, this investigation found communities in areas with a lower precipitation trend (unreliable rainfall) and with higher malaria susceptibility were less aware of BGP; the areas that stand to benefit most from the technique are less likely to have heard of BGP. This research therefore suggests that NGOs and the GoM should focus their work on expanding the awareness of BGP to such areas over the coming years.

Community management of boreholes has the capacity to provide a sustainable and empowering method of waterpoint management, reducing the reliance on external NGOs and government input [78]. However, concerns have been raised regarding community's capacity to reliably manage water-points [13,79,80]. Indeed, this study found that 35.2% (28,560) of water-points surveyed reported being partial or non-functionality. Using proceeds from BGP to maintain boreholes provides an innovative solution to many of the challenges communities face in the management of boreholes [20]. Collaboration between stakeholders in sustainable agriculture and water management in Malawi is well established [9], this research highlights that collaboration between stakeholders in waterpoint management and those involved in BGP is also necessary in maximising the benefits and extent of BGP practise. Currently, areas with preventative maintenance performed on the water-points are significantly less likely to have heard of BGP, despite these water-points with greater external input. Engaging service providers responsible for borehole maintenance in spreading awareness of BGP and how to access training provides one method of ensuring increasing synergy between borehole management practises.

It is well established that social ties represent a critical consideration in the adoption of sustainable practises [26-29]. Throughout the process of the promotion of BGP, the value of neighbours and community ties cannot be underestimated. The proximity to neighbours practising BGP was not found to be a significant variable in where BGP was adopted in communities aware of it; this is despite this having been shown to be a significant variable in the adoption of other sustainable agricultural techniques [28,29]. This may partially be a reflection that social ties are more complex than merely a product of proximity [73]. However, proximity to a borehole-practising waterpoint was a significant variable in which communities were aware of

BGP, highlighting the importance of social networks in the sharing of information [73,74]. Furthermore, neighbours represented the main way in which surveyed water-points reported being aware of BGP. NGOs and governments could capitalise on this resource by equipping communities to educate neighbouring communities about sustainable practices. Similar examples of practices have been seen in the promotion of sustainable agricultural practises elsewhere; for example, the Ethiopian government implemented an agricultural extension model bringing together a 'role model farmer' with four neighbouring farmers to promote social learning [29].

5. Conclusions

Combining qualitative and quantitative data collected in an extensive survey of over 100,000 water-points across Malawi [13,14,38,39], this research developed understanding of the status of BGP adoption in Malawi. Building on literature reporting the adoption of sustainable agricultural practises [20,26-29,42,43,45,71], this study identified some of the variables influencing where BGP is adopted and whether communities were aware of BGP by investigating socioeconomic, biophysical and waterpoint specific variables [44].

5.1. A New Focal Area for BGP Promotion

43.0% of communities surveyed had an awareness of BGP. However, despite inputs from the GoM and many NGOs, BGP was practised at just 2.4% of the water-points investigated. The knowledge and uptake of BGP were dependent on a range of socioeconomic, biophysical, and waterpoint specific factors. This study highlighted areas where communities could benefit most from BGP, due to unreliable rainfall and high malaria susceptibility, were less likely to be aware of BGP. This research provides key policy recommendations suggesting that NGOs and the GoM should focus their work on expanding the awareness of BGP to these communities over the coming years.

5.2. Context Is Key

Although the encouragement of sustainable techniques such as BGP are highly beneficial, they cannot be considered in isolation. The encouragement of BGP should be considered alongside other principles in waterpoint management such as the development of an established waterpoint committee and ensuring maintenance and proper functioning of water-points [78]; waterpoint functionality and waterpoint committee structure were key variables in the adoption of BGP. BGP adoption must also be considered in the context of the specific community and waterpoint, accounting for limitations in the context such as land ownership challenges or conflicting priorities for land and water usage such as live- stock. However, the context of communities may also present an invaluable asset through pre-established social capital. Capitalising upon social contacts both between neighbouring communities and external service providers could provide an efficient mechanism of expanding the awareness of BGP in Malawi [26-29].

5.3. Future Directions

Ensuring the most effective method for the promotion of BGP will not only be critical in ensuring the maximal benefit of this technique but also provides key lessons in understanding the adoption of other sustainable techniques in Malawi. With pressure on Malawi's water resources projected to increase due to climate change [5,6], population growth [7] and agricultural intensification [1] understanding sustainable practises will be critical in achieving SDG2 [17] and SDG6 [16] (zero hunger and access to clean water and sanitation respectively). Furthermore, the proposals for the expansion of small-holder farmer cooperatives in Malawi's agricultural development [25] emphasise the need for understanding community decision making in sustainable land and water management. Investigating factors influencing the awareness and adoption of BGP in Malawi provides one example of community management of land and water. Exploring community awareness and adoption of other sustainable techniques in Malawi's land and water management will further guide policy makers and stakeholders in the promotion of sustainable practices.

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Institutional Review Board Statement: The study was approved by the Ethics Committee of the Government of Malawi.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study. All data collected was in line with the Government of Malawi ethics and was agreed with each interviewee.

Data Availability Statement: Confidential data was obtained from the Government of Malawi. Additional data was obtained from the publicly accessible repository RCMRD and is described within the Appendix A.

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Conflicts of Interest: The authors declare no conflict of interest

Appendix A

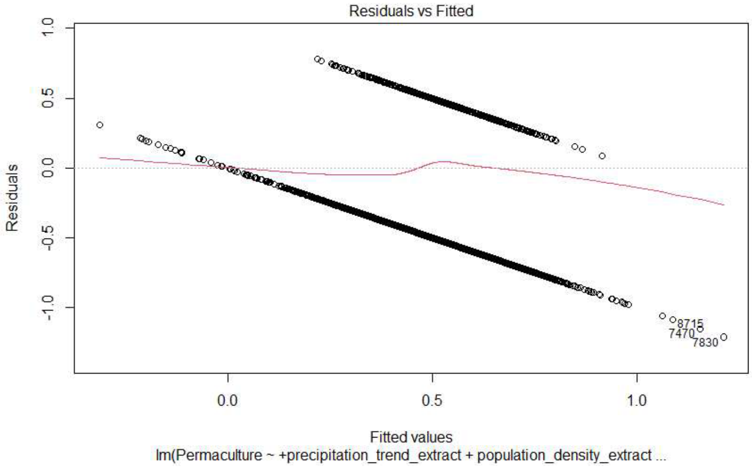


Figure Al. Residuals vs fitted for GLM model of where BGP is adopted in cases where communities are aware of BGP.

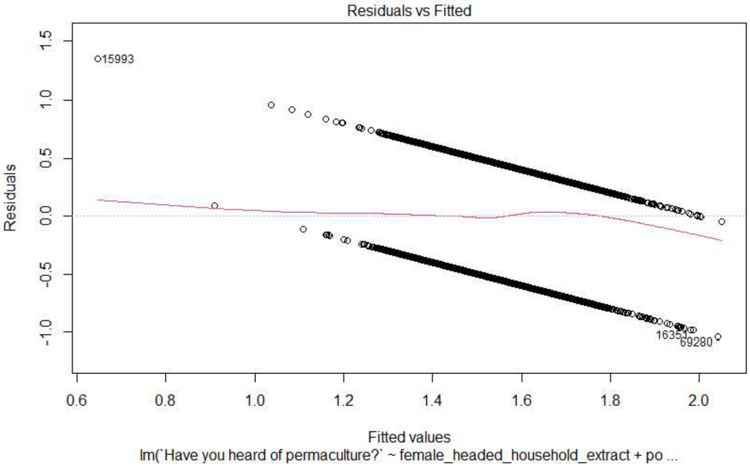


Figure A2. Residuals vs fitted plot for GLM model of communities have been aware of BGP.

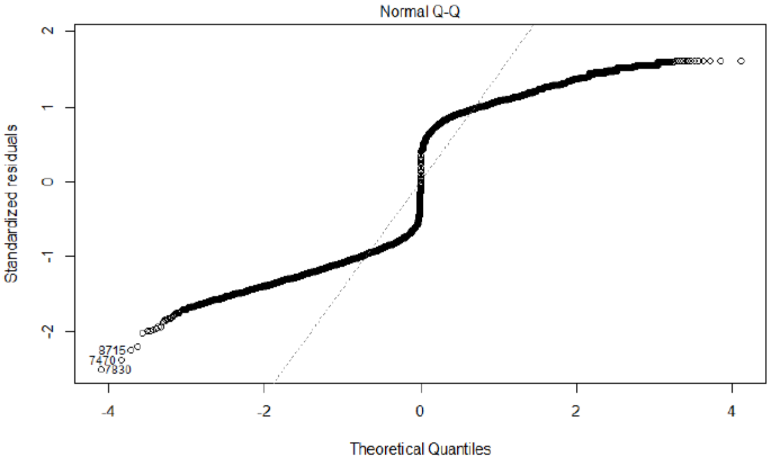


Figure A3: Q-Q plot for GLM model of communities have been aware of BGP.

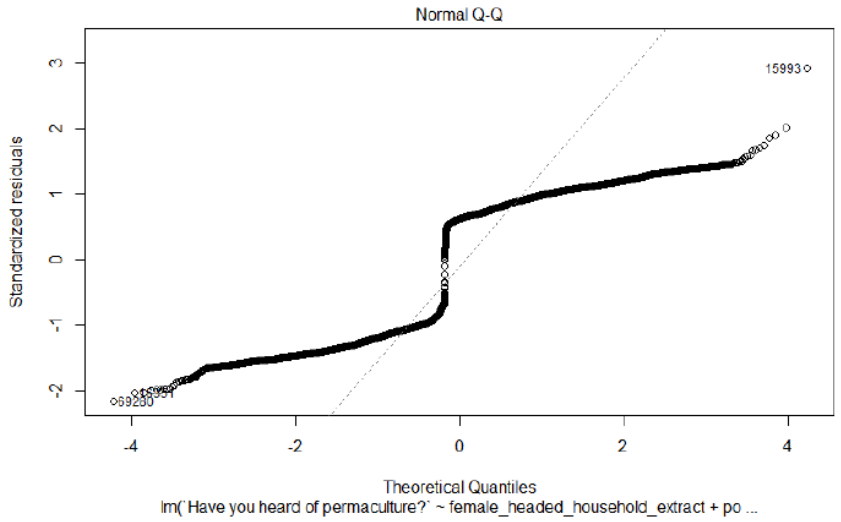


Figure A4: Q-Q plot for GLM model of where BGP is adopted in cases where communities are aware of BGP.

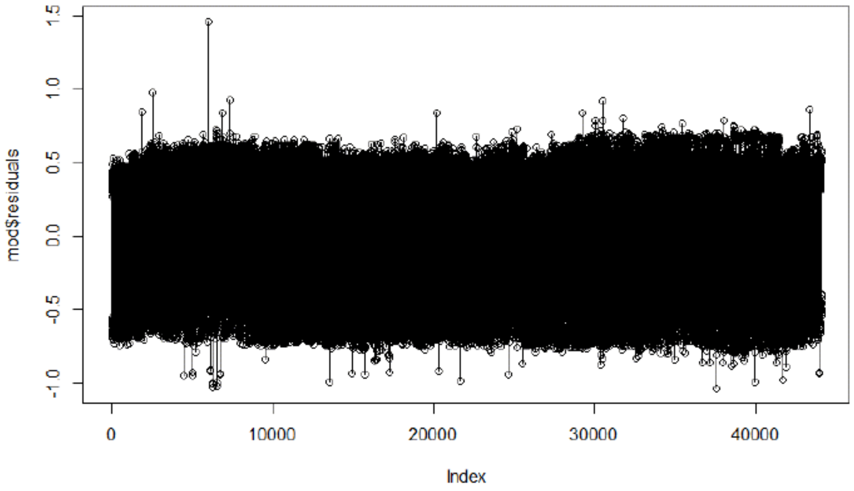


Figure A5: Residuals plot for GLM model of communities have been aware of BGP.

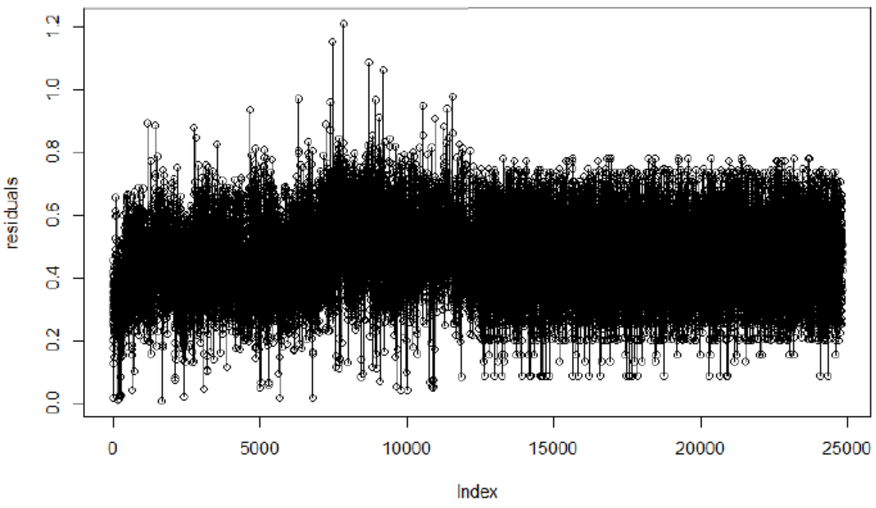


Figure A6: Residuals plot for GLM model of where BGP is adopted in cases where communities are aware of BGP.

Table A1. Variance inflation factor (VIF) for variables incorporated the GLM of where BGP has been heard of.

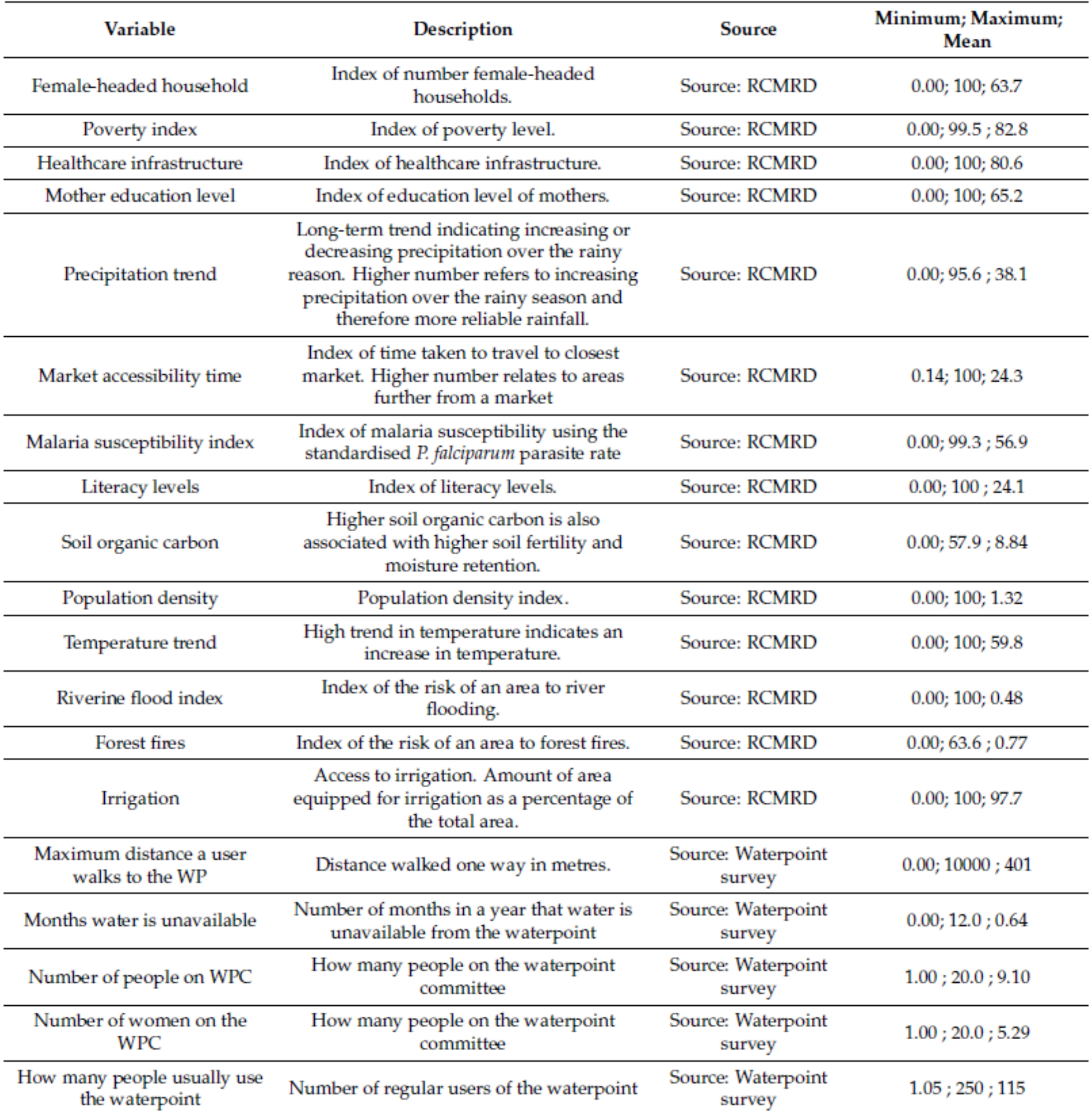
Variable	**VIF Value**
Number of women on the Waterpoint Committee	1.03
Preventative maintenance performed on the waterpoint	1.07
How many people usually use this waterpoint	1.09
Female-headed household	2.31
Soil organic carbon	1.29
Malaria susceptibility	2.13
Distance from other waterpoint practising BGP	2.22
Poverty	1.21
Mother education	1.43
Precipitation trend	1.39
Tariff or user fee for water use	1.07
Irrigation	1.07
Riverine flooding	1.02

Market accessibility time	1.21
Maximum distance a user walks to this waterpoint	1.08

Table A2. Variance inflation factor (VIF) for variables incorporated the GLM of where BGP is practised where communities are aware of it.

Variable	**VIF Value**
How many women are on the Waterpoint Committee	1.02
Preventative maintenance performed on the waterpoint	1.05
Precipitation trend	1.16
Maximum distance a user walks to this waterpoint	1.04
Market accessibility time	1.18
How many months water is not available	1.04
Population density	1.05
Riverine flooding	1.01
Healthcare infrastructure	1.39
Soil organic carbon	1.61
Mother education level	1.44
Female-headed household index	1.58
Temperature trend	1.52

Table A3. Summary of quantitative variables, description, values and their sources.



Variable	Description	Source	Minimum; Maximum; Mean
Female-headed household	Index of number female-headed households.	Source: RCMRD	0.00; 100; 63.7
Poverty index	Index of poverty level.	Source: RCMRD	0.00; 99.5 ; 82.8
Healthcare infrastructure	Index of healthcare infrastructure.	Source: RCMRD	0.00; 100; 80.6
Mother education level	Index of education level of mothers.	Source: RCMRD	0.00; 100; 65.2
Precipitation trend	Long-term trend indicating increasing or decreasing precipitation over the rainy reason. Higher number refers to increasing precipitation over the rainy season and therefore more reliable rainfall.	Source: RCMRD	0.00; 95.6 ; 38.1
Market accessibility time	Index of time taken to travel to closest market. Higher number relates to areas further from a market	Source: RCMRD	0.14; 100; 24.3
Malaria susceptibility index	Index of malaria susceptibility using the standardised *P. falciparum* parasite rate	Source: RCMRD	0.00; 99.3 ; 56.9
Literacy levels	Index of literacy levels.	Source: RCMRD	0.00; 100 ; 24.1
Soil organic carbon	Higher soil organic carbon is also associated with higher soil fertility and moisture retention.	Source: RCMRD	0.00; 57.9 ; 8.84
Population density	Population density index.	Source: RCMRD	0.00; 100; 1.32
Temperature trend	High trend in temperature indicates an increase in temperature.	Source: RCMRD	0.00; 100; 59.8
Riverine flood index	Index of the risk of an area to river flooding.	Source: RCMRD	0.00; 100; 0.48
Forest fires	Index of the risk of an area to forest fires.	Source: RCMRD	0.00; 63.6 ; 0.77
Irrigation	Access to irrigation. Amount of area equipped for irrigation as a percentage of the total area.	Source: RCMRD	0.00; 100; 97.7
Maximum distance a user walks to the WP	Distance walked one way in metres.	Source: Waterpoint survey	0.00; 10000 ; 401
Months water is unavailable	Number of months in a year that water is unavailable from the waterpoint	Source: Waterpoint survey	0.00; 12.0 ; 0.64
Number of people on WPC	How many people on the waterpoint committee	Source: Waterpoint survey	1.00 ; 20.0 ; 9.10
Number of women on the WPC	How many people on the waterpoint committee	Source: Waterpoint survey	1.00 ; 20.0 ; 5.29
How many people usually use the waterpoint	Number of regular users of the waterpoint	Source: Waterpoint survey	1.05 ; 250 ; 115

Table A4. Summary of binary response variables.

Variable	Number of "Yes" Responses	Number of "No" Responses
Is preventative maintenance performed on the waterpoint? Source: Waterpoint survey	48,100	16,100
Is there a tariff or user fee for the waterpoint? Source: Waterpoint survey	51,400	13,900

GLM with all variables for where BGP has been heard of

Table A5. Results of generalised linear regression model for variables influencing where BGP has been heard of in Malawi combining all analysed variables. BIC Value: 13,960.35. AIC Value:

13,786.31. The model correctly predicted 59.83% of cases where BGP had been heard of (18,565 correct predictions and 12,462 incorrect predictions). Significant p values are marked with one or more asterisk(*). Significance codes: *** (0 < p ::::; 0.001); ** (0.001 < p ::::; 0.01); * (0.01 < p ::::; 0.05).

Variable	**Variable Estimate** (x0.001)	**Significance**
Female-Headed Household	+16.2 ± 1.02	***
Poverty	+ 10.6 ± 1.48	***
Healthcare infrastructure	-0.928 ± 1.03	NS
Mother education level	+3.84 ± 0.393	***
Precipitation trend	+6.71 ± 0.891	***
Market accessibility time	+2.27 ± 0.591	***
Malaria susceptibility	-11.3 ± 0.793	***
Literacy level	+1.76 ± 1.57	NS
Soil organic carbon	-29.2 ± 3.11	***
Population density	-13.5 ± 4.91	**
Temperature trend	+0.0418 ± 1.57	NS
Riverine flood	-12.8 ± 2.90	***
Maximum distance a user walks to the WP	+0.0601 ± 0.0228	**
Distance to a BGP practising WP	-158.8 ± 12.46	***
Forest fires	+7.16 ± 2.78	*
Irrigation	+8.62 ± 1.74	***
Number of months water not available	+1.55 ± 7.42	NS
How many people are on the WPC	-9.45 ± 6.93	NS
How many women are on the WPC	-8.15 ± 8.07	NS
How many people usually use this WP	0.121 ± 0.0217	***
Preventative maintenance performed	120 ± 25.7	***
Tariff or user fee for water use	-149 ± 30.6	***

Table A6. Results of generalised linear regression model for variables influencing where BGP is practised in places aware of BGP. BIC Value: 33000. AIC Value: 32800. Correctly predicted the status of which boreholes adopted BGP in 53.6% of cases (3006 correct predictions and 2599 incorrect predictions). Sensitivity 0.647, specificity 0.530. Significant p values are marked with one or more asterisk(*). Significance codes: *** (0 < p ::::;0.001); ** (0.001 < p ::::; 0.01); * (0.01 < p ::::; 0.05).

Variable	**Variable Estimate** (x0.001)	**Significance**
Female-Headed Household	-8.60 ± 1.29	***
Poverty	+8.43 ± 2.29	***
Healthcare infrastructure	+2.61 ± 1.35	NS
Mother education level	+4.25 ± 0.508	***
Precipitation trend	+19.7 ± 1.29	***
Market accessibility time	+3.32 ± 0.777	***
Malaria susceptibility	+2.458 ± 1.11	*
Literacy level	-3.78 ± 2.29	NS
Soil organic carbon	+46.9 ± 4.06	**
Population density	-27.0 ± 9.54	**
Temperature trend	+9.04 ± 2.09	***
Riverine flood	-74.5 ± 13.0	***

Table A6. *Cont.*

Variable	Variable Estimate (x0.001)	Significance
Maximum distance a user walks to the WP	+0.355 ± 0.0284	***
Distance to a BGP practising WP	+9.22 ± 15.7	NS
Forest fires	-2.01 ± 3.53	NS
Irrigation	+11.4 ± 2.54	***
Number of months water not available	-125 ± 11.1	***
Number of people on the WPC	+12.6 ± 9.24	NS
Number of women on the WPC	+99.2 ± 1.00	***
Number of people usually use this WP	-0.125 ± 0.0257	***
Preventative maintenance performed	-95.7 ± 33.6	**
Tariff or user fee for water use	-44.9 ± 41.5	NS

Table A7. Reasons given for rejection of BGP by communities who became aware of BGP but were not practising the technique.

Reason for BGP Rejection	Incidence
No common land at end of soakway	13,000
Not interested	7070
Lack of knowledge/ awareness/ no community training	4310
Limited water/nonfunctional waterpoint	2380
Limited money	981
No access to seeds	712
Yet to start/ temporary pause	649
Animals	497
Salty water/poor water quality	457
River nearby /natural irrigation	64.0
Not allowed by health ministry /WUA/bylaws	44.0
New borehole/under construction	38.0
Unsuitable conditions	37.0
Not allowed by landowner	35.0
Conflict/ disagreement	32.0
Close to dambo / use special dambo	27.0
No soakway/ drainage at borehole	27.0
Vandalism/ abuse of garden	26.0
Theft	25.0
Work overload	25.0
Borehole located in a school	19.0
People use their own gardens	16.0
Committee is changing/new/ disorganised/not present	13.0
No security	13.0
Bills/ charges	10.0

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7.2.1 Postface

This piece answered RQ4, meeting SO11 through the investigation of the sustainable water-use technique borehole-garden permaculture. The adoption of borehole garden permaculture is an example of a local solution to challenges of both water quantity (as discussed in Chapter 4), by the promoting sustainable groundwater use, and water access, by financing borehole maintenance and combating the significant challenge of borehole non-functionality within Malawi (Kalin et al., 2019). The solution focuses on adoption of the technique by water-point committees, local actors in water resource management. Not only does this technique address challenges in water access (SDG6), but the technique also improves health and wellbeing (SDG3) and food security (SDG2). Yet despite large benefits and relatively high awareness of the technique, BCP is poorly adopted nationally. The work emphasised the significance of considering context and leveraging social capital in encouraging community engagement when promoting sustainable techniques in water management.

7.3 Evaluation of pit-latrine emptying practices as a solution to poor pit-latrine construction quality: the case of Malawi

Rebekah G.K. Hinton[1, 2*], Modesta Kanjaye[3], Christopher J.A. Macleod[2], Mads Troldborg[2], Robert M. Kalin[1]

[1] Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow UK; Rebekah.hinton@strath.ac.uk (R.G.K.H.); Robert.Kalin@strath.ac.uk (R.M.K.)
[2] The James Hutton Institute, Craigiebuckler, Aberdeen AB15 8QH, UK; kit.macleod@hutton.ac.uk (C.J.A.M.); mads.troldborg@hutton.ac.uk (M.T.)
[3] Ministry of Water and Sanitation, Government of Malawi, Private Bag 390, Lilongwe, Malawi; modesta.banda@gmail.com M.K.))

* Correspondance : Rebekah.hinton@strath.ac.uk;

Abstract: The importance of safe sanitation provision is crucial for achieving Sustainable Development Goal 6 (SDG6), which aims to ensure access to adequate and equitable sanitation and hygiene for all. Progress towards safely managed sanitation, particularly in Malawi, is held back by low-quality sanitation provision, leading to frequent collapse of pit-latrines and groundwater contamination risks. A national survey of 268,180 latrine facilities in Malawi was evaluated to explore the implications of their construction to the sustainability of sanitation provision. The adoption of pit-latrine emptying was evaluated revealing a low level of pit-latrine emptying (1.3% of pit-latrines) and significant variation in emptying practice. Three scenarios of pit-latrine construction and management were evaluated, comparing the costs of current practices in sanitation provision to shifting to a system of high-quality sanitary facility provision, investigating whether pit-latrine emptying could make higher quality construction more achievable. The analysis found that high-quality pit-latrines that were emptied had the longest lifespan (13.6 years), in comparison to the default management of low-quality pit-latrine construction and no emptying (4.5 years); current practices of low-quality pit-latrines that are not emptied create stranded assets in sanitation development. Currently, the high cost of pit-latrine emptying outweigh the financial benefits of an extended lifespan, and reduced frequency of construction. For pit-latrine emptying to make higher quality construction more affordable, we calculate that the cost of emptying would need to be halved. Promotion of affordable pit-latrine emptying services, coupled with regulatory measures and cultural considerations could enhance sanitation access while mitigating the financial burden on users, and reducing the risks of groundwater contamination.

Keywords: Sanitation, open defecation, stranded asset, circular economy, sustainable

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Introduction

Pit-latrines are the major solution for sanitation in many low- and middle-income countries and are crucial to meet the sanitary needs of over 1.8 billion people globally (Gwenzi et al., 2023). Ending open defecation is a global priority, as outlined in SDG6 which aims to end of open defecation by 2030 (UN General Assembly, 2015). As global efforts continue to push towards ensuring sanitation provision pit-latrine usage is anticipated to increase (Gwenzi et al., 2023). Furthermore, high population growth in many of the countries most dependent on pit-latrines will further increase international pit-latrine usage (Gwenzi et al., 2023).

Whilst pit-latrines present a critical sanitary provision, growing dependency raises concerns of significant consequences for groundwater quality. Unless appropriately managed, pit-latrines can result in groundwater contamination (Banks et al., 2007; Graham & Polizzotto, 2013; Tillett, 2013; Wright et al., 2013). This presents a particular public health concern in contexts where there is an intersection of high pit-latrine dependency and high reliance on groundwater, often untreated, for drinking water provision (Graham & Polizzotto, 2013). Maintaining appropriate distancing between pit-latrines and water points is the major mechanism by which pit-latrine contamination of drinking water is managed (Franceys, 1992; Graham & Polizzotto, 2013; Sphere Association, 2018). But continuing to ensure appropriate distancing becomes more challenging with population growth and urbanization (Hinton et al., 2023a; Kariuki, 2003). Consequently, appropriate management techniques to minimise the contamination risk from pit-latrines are essential (Strauss & Montangero, 2004).

Alongside high population growth and urbanisation resulting in increasing densities of pit-latrines, a high frequency of pit-latrine abandonment further adds to high pit-latrine density (Hinton et al., 2023b; Kariuki, 2003). In Malawi, for example, it is estimated that there will be over 30 million pit-latrines filled and abandoned by 2070 (Hinton et al., 2023b). Principle causes of abandonment of pit-latrines are collapse (Mosler et al., 2018; Namwebe et al., n.d.), often due to heavy rainfall as well as poor construction quality, and the pit-latrine filling up with waste (Hinton et al., 2023b; Nakagiri et al., 2016.). Latrines are often left abandoned without proper treatment of the faecal waste, they therefore continue to pose a risk to groundwaters and public health. Collapse of latrines can also result in a return to open defecation for users who are unable to afford to replace the collapsed facility, presenting a danger of reversal in progress towards eliminating open defecation (Cavill et al., 2015; Kouassi et al., 2023; Mosler et al., 2018). Not only does pit-latrine collapse raise public health concerns, it also represents a major loss of investment in sanitation infrastructure, presenting a stranded asset in Water, Sanitation and Hygiene (WaSH) provision (Hinton et al.,2024 *,* Kalin et al., 2019*)*.

Pit-latrine construction quality is a pivotal factor, alongside contextual considerations such as soil type and weather, in managing the risk of collapse and long-term sustainability of improvements in sanitation access. Lining latrines can improve structural integrity, reducing the risk of collapse (Namwebe et al., n.d.; Reed, 2014). It is recommended that the top 0.5 to 1.0 metre of the pit is always lined to support structural integrity but this may be dependent on soil type (Reed, 2014). Common and recommended lining materials are bricks and timber, although alternative materials such as oil drums and sandbags are also used (Reed, 2014). Bamboo and cane, though used, are only recommended for pit-latrines with intentionally very short lifespans of under 2 years (Reed, 2014). Covering the floor of the latrine with a concrete slab is also promoted to increase both structural integrity and improve hygiene (Reed; Bob, 2014). The importance of a slab to facilitate appropriate hygiene and that the sanitary facility is safe is emphasised in that it is a requirement for pit-latrines to have slabs to meet the standard of safely managed sanitation services under SDG6.2 ‘access to adequate and equitable sanitation and hygiene for all' (UN General Assembly, 2015). Not only does appropriate lining and construction ensure long-term sustainability of sanitary infrastructure, minimising the risk of collapse, but also the lining of pit-latrines provides an important way to minimise faecal groundwater contamination (Graham & Polizzotto, 2013; Gwenzi et al., 2023; Masindi & Foteinis, 2021). Despite the importance of appropriate pit-latrine construction, ensuring quality construction is often insufficiently emphasised in the promotion of pit-latrine usage resulting in often short-lived improvements in sanitary access (Kouassi et al., 2023). As dependency on pit-latrines continues, consideration of construction quality is essential to minimise many of the drawbacks of pit-latrine usage including reducing contamination, and the risk of collapse.

Malawi presents a context in which appropriate pit-latrine management is especially challenging. Significant progress has been made in the reduction of open defecation, largely through the promotion of pit-latrines (Hinton et al., 2023b; NSO, 2019). A high rate of population growth, with an annual growth rate of 2.6% (World Bank), results in a increasing demand for sanitation infrastructure (Hinton et al., 2023b). Yet such sanitation infrastructure presents a challenge to groundwater, the main source of drinking water in Malawi (Graham & Polizzotto, 2013). Over 60% of the population's source of drinking water is reported to have *E. coli* contamination, partially due to relaxed water quality standards for rural water supplies such as hand pumps (NSO, 2021). Pit-latrine usage is an area of concern for groundwater quality and has been linked to high levels of groundwater contamination in Malawi (Rivett et al., 2022). Furthermore, pit-latrine contamination risks to groundwater are forecast to increase largely due to the combination of population growth and urbanisation (Hinton et al., 2023a). Not only are risks posed from an increasing number of pit-latrines being used, the high rate of abandonment of pit-latrines raises a growing concern of contamination from an ever-increasing pool of abandoned pit-latrine facilities; from 2020-2070 there are forecast to be over 30 million pit-latrines filled and abandoned within Malawi which may to continue to serve as point-sources of contamination (Hinton et al., 2023b).

The high risk of collapse of pit-latrines also plagues Malawi's sanitation provision. Improvements in reducing open defecation through pit-latrine construction are often short lived, partially due to a loss of sanitation facilities without being replaced (Hinton et al., *in review).* This has been seen on both a local level, with areas previously declared open defecation free returning to open defecation (Hinton et al., *in review),* as well as a national level with an increase in open defecation from 6.2 percent in 2016 to 6.7 percent in 2022 (NPC, 2022). Growing pressure on sanitary provision due to high population growth and urbanisation, coupled with an increasing risk of extreme weather events, presents a challenging prospect for long-term progress to SDG6.2 with the danger of worrying trends in increases of open defecation practice continuing (Hinton et al., 2023b). Yet despite their drawbacks, pit-latrines remain the crux of Malawi's drive to provide safe sanitation (NPC, 2022). As such, ensuring appropriate pit-latrine planning and usage is essential.

Despite the need for high quality sanitation construction, progress for provision of safely managed sanitation services is slow, both worldwide **(**UNICEF & WHO, 2020**)**, and within Malawi (Hinton et al., 2023b). Calls to push for higher quality pit-latrine construction standards are hampered by the high costs of improved facilities (Daudey, 2018; Mamo et al., 2023; Peletz et al., 2017) and often low willingness to pay (Peletz et al., 2017). There is a need to evaluate systems with the potential to reduce the financial burden of higher quality sanitation.

Pit-latrine emptying presents a potential solution to the many intersecting challenges of high pit-latrine dependency. By removing waste from the latrine and preventing the latrine filling up, emptying sanitary facilities can extend the lifetime of the latrine (Mubatsi et al., 2021) and reduce the spatial repercussions of pit-latrine abandonment (Jenkins et al., 2015; Kariuki, 2003). Frequent emptying can also minimise groundwater contamination (Gwenzi et al., 2023). Latrines are emptied either manually, using shovels and buckets, or mechanically utilising vacuum tanker trucks and pumps (Burt et al., 2019; Chipeta et al., 2017; Thye et al., 2009). Waste from faecal sludge can be treated at wastewater treatment facilities or through solutions that provide circular economy utilisation of faecal waste including in the production of organic fertiliser and biochar (Midega, 2022). Safe pit-latrine emptying practices require pit-latrines to be lined (Holm et al., 2018; Rochelle et al., 2015) making it inappropriate for many facilities but posing the possibility of the coupled promotion of higher-quality pit-latrine construction and emptying practices to jointly reduce pit-latrine collapse and contamination risks alongside extending pit-latrine lifespans. Despite the benefits of pit-latrine emptying practices there are no national level evaluations of pit-latrine emptying within Malawi, with a few studies that have explored emptying on a highly localised scale finding significant variation in prices, practices, and performance (Chipeta et al., 2017; Rochelle et al., 2015; WAC, n.d.)

Here we examine the feasibility of pit-latrine emptying and high-quality pit-latrine construction as a solution to the multifaceted challenges of pit-latrine reliance, exploring whether pit-latrine emptying services in Malawi could reduce the financial burden of higher quality pit-latrine construction on households. By developing stakeholder informed scenarios of faecal management practices, we explore the economic feasibility of the drive to higher quality pit-latrine construction in Malawi. Specifically, we address the following research questions: (1) Are pit-latrine emptying practices able to extend pit-latrine lifespan? (2) How is pit-latrine emptying being carried out in Malawi? (3) Can pit-latrine emptying provide an economically viable system to promote higher quality pit-latrine construction in Malawi?

Materials and Methods

Study area

Malawi is a South-East African country, Figure 1, with a population exceeding 20 million (World Bank). The country is undergoing high population growth, with the population projected to exceed 30 million by 2040 and 54 million by 2070 (KC & Lutz, 2017). Currently, around 23% of the population has access to improved sanitation (Hinton et al., 2023b), the Government of Malawi aims to ensure 100% access to safely managed sanitation (an improved, non-shared sanitation facility) by 2060 (NPC, 2021.). Pit-latrines provide the main form of sanitation and are used by over 90% of the population (Hinton et al., 2023b). These have been linked to contamination of groundwater (Graham & Polizzotto, 2013.; Hinton et al., 2023a; Rivett et al., 2022) a major source of drinking water, with over 60% of improved sources of drinking water coming from boreholes and tubewells (NSO, 2021). Boreholes and tubewells have high levels of contamination; over 60% of borehole-s have *E. coli* contamination (NSO, 2021). In addition, high levels of non-functionality limit water access; 40% of boreholes are partially or completely non-functional (Hinton et al., 2021.; Kalin et al., 2019). Inappropriate provision of Water, Sanitation, and Hygiene (WaSH) places a significant health burden on the country, 52% of outpatients are estimated to seek treatment for water and sanitation related diseases (Chavula, 2021). This was further underscored in 2023 by Malawi's most deadly cholera outbreak with widespread drinking water contamination being suggested as the major reason for severity of the outbreak (Sokemawu Freeman et al., 2024).

Rapid urbanisation is also shaping Malawi's population demographics. Currently, 16% of the population resides in urban areas, this is projected to increase to 60% by 2063 (NPC, 2021). Most of the existing urban population reside in informal slum areas (NPC, 2021.). High poverty limits the potential for improved access to sanitation with over 70% of the population living below the international poverty line of $2.15 per day (World Bank).

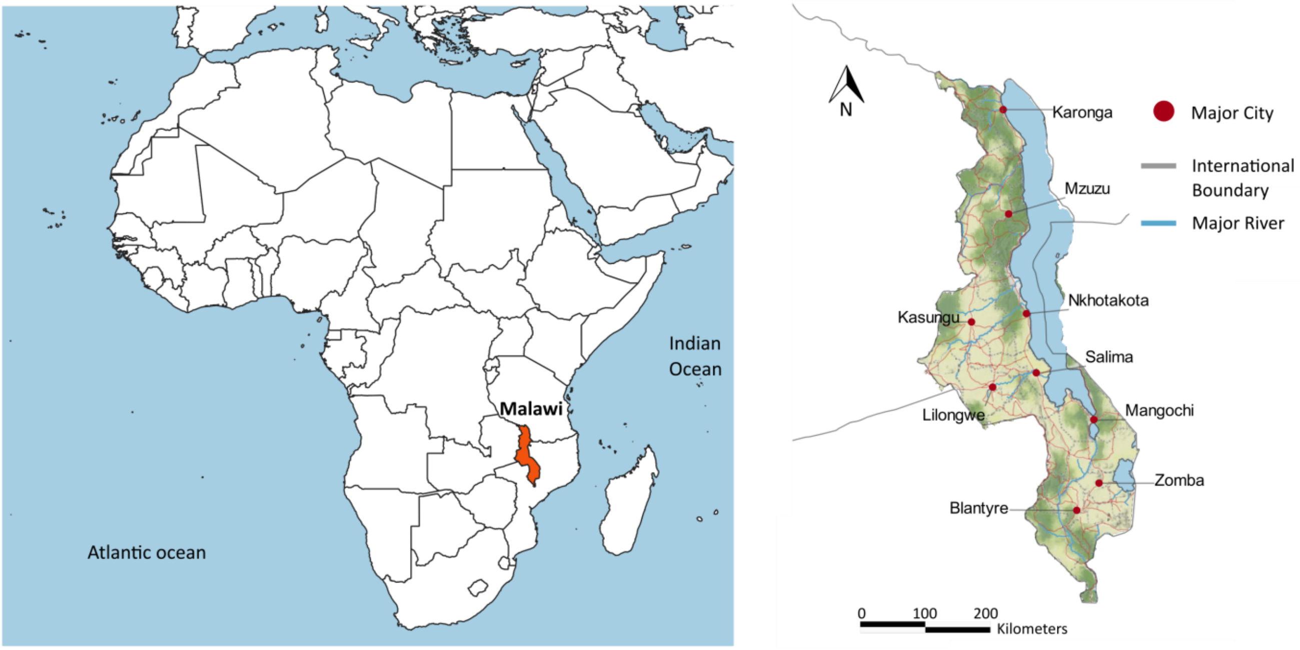

Figure 8: Map of study location, Malawi, with major cities and rivers shown. Image made with QGIS using Stamen Terrain background.

Study design

A national survey of sanitary facilities, across Malawi, was conducted by the Government of Malawi through the Scottish Government Climate Justice Fund Water Future Programme. A total of 268,180 sanitation facilities were surveyed by trained Government of Malawi surveyors with surveys conducted in Chichewa and English. Responses were recorded and hosted on the online platform mWater (mWater). Surveys investigated the type of facility, condition, typical usage, and the management of the facility (notably emptying procedures). The types of facility categorised in the survey were: Flush/ pour flush toilet, Ventilated Improved Pit (VIP) latrine, Pit-latrine without slab, composting toilet, hanging toilet/ latrine, pit-latrine without slab/ open pit, bucket, and other. Whether latrines were lined was asked as an additional question.

Questions were also asked regarding previously abandoned facilities that had been replaced by the surveyed latrine. Following data collection, all responses were quality controlled by the University of Strathclyde. Additional data cleaning was implemented to remove duplicate sites (where multiple visits through time were undertaken). This study is restricted to responses to surveys conducted between 2018–2019, resulting in 201,782 responses. Only data related to pit-latrines (VIP latrines and pit-latrine with/ without slab) was investigated, these made up the majority of responses with 201,381 complete pit-latrine surveys analysed.

Quantitative data analysis

All prices were taken as 2019 Malawian Kwacha (MK), 2024 US Dollar (USD) equivalents were calculated accounting for the devaluation of MK from 2019 and the 2024 exchange rate.

Data on the cost and frequency of emptying was collected within a given bracket (range) of costs/ frequencies. The average cost and frequency of emptying was calculated by taking the average cost/ frequency for each bracket. For the upper price bracket (>20,00 MK, 2019), the maximum cost of pit-latrine emptying was taken as 40,000 MK (2019) (personal correspondence). For a pit-latrine emptying frequency of more than 3 years, the maximum pit-latrine emptying frequency taken was 15 years, based on literature estimates of pit-latrine emptying frequency (Jenkins et al., 2015). Average costs and frequencies were calculated based on the service provider. Standard error was calculated as the standard deviation divided by the root sample error for each service provider group.

Data on the cost of construction and risk of collapse was analysed by sanitary facility type. Construction costs were provided as brackets of cost, to calculate the average cost, the average price within each price bracket was taken and mean construction costs for each type of facility calculated. Standard error was calculated for each cost as the standard deviation divided by root sample number. To estimate the average costs for the upper bracket (>50,000 MK, 2019), a maximum cost of 100,000 MK (2019) was estimated based on stakeholder consultation.

To evaluate the risk of collapse based on the pit-latrine construction, the number of facilities that were partially or fully collapsed (including those still in use) as well as the number of facilities that were partially or fully collapsed (but not in use) were calculated for each construction type. Two-sided t-tests (5% significance level) were used to determine whether there was a statistically significant greater collapse risk between groupings.

To further evaluate the risk of collapse, and subsequent abandonment, based on construction, the reasons for pit-latrine abandonment were evaluated. The analysis focussed on whether pit-latrines were primarily abandoned due to collapse or filling up, the most common causes of abandonment (Hinton et al., 2023b), based on their construction type. Respondents listed any reasons why facilities had been abandoned as qualitative responses. Content analysis was used to sum the totals number of facilities where collapse from rainfall had contributed to why the facility was abandoned as well as cases where the latrine filling up had contributed to abandonment, these were then broken into cases where the facility were pit-latrines with and without slabs (the most common latrines). Data was not available on the lining of abandoned facilities.

Pit-latrine management scenarios

Stakeholder consultation with policymakers at the Ministry of Water and Sanitation was undertaken through a consultation meeting discussing challenges in sanitation provision and pit-latrine construction quality (January 2024). The meeting informed understanding of the current ‘standard trajectory of sanitation development within Malawi, which continues construction of low-cost ‘starter’ pit-latrines (pit-latrines without slabs and unlined) to provide sanitation and end open defecation (UNICEF, 2018). The meeting then identified an ‘aspirational’ trajectory of sanitation provision in which higher-quality sanitary facilities are constructed (pit-latrines with slabs and lined) with the mutual benefit of longer lifespan and reduced groundwater contamination. Stakeholder consultation then discussed whether pit-latrine emptying could provide a method to subside higher-quality pit-latrine construction. This led to the formulation of three pit-latrine management scenarios which are discussed here.

Scenario A is a ‘standard’ pit-latrine management scenario in which unlined pit-latrines without a slab, the most common type of pit-latrine (Hinton et al., 2023b), are constructed and replaced when filled/ collapsed. Pit-latrines are assumed to be, on average, half-filled at the time of collapse. This is most like the current practice of faecal management in Malawi. We assume the average cost, fill-up rate and frequency of collapse for unlined pit-latrines without a slab.

Scenarios B and C are based on calls for increased access to improved sanitation facilities, as discussed with stakeholders. Scenario B proposes a pit-latrine emptying scenario in which high-quality (lined and with a slab) pit-latrines are constructed and regularly emptied, pit-latrines are therefore only replaced upon collapse. Scenario C proposed a scenario of high-quality (lined and with a slab) pit-latrine construction with no pit-latrine emptying. We assume the average cost, fill-up rate and frequency of collapse for lined pit-latrines with a slab, as improved facilities, for Scenarios B and C.

Estimates of average construction costs, time taken to fill, time taken to collapse, and the ratio of collapse to filling as reasons for abandonment were calculated for the different types of pit-latrines constructed under the Scenarios. The average cost and frequency of pit-latrine emptying was also used for calculating average costs for the scenarios. These are all summarised in appendix table 2. Other maintenance costs, notably repairs, cleaning, and supplies are assumed to be equal between the two scenarios and therefore are not included in the comparative analysis.

Qualitative content analysis

Qualitative content analysis was applied to investigate the responses to the questions ‘Why has this pit-latrine been abandoned’ and ‘Why hasn’t the pit-latrine been emptied?’ For pit-latrine abandonment, respondents listed multiple reasons chosen from a list of suggested responses. For the purposes of this study cases which listed that the pit-latrine had been abandoned as it had "Collapsed due to rainfall” and “It has filled up" were counted. This was used to provide an indication of the relative frequency of fill up and collapse for multiple types of sanitary facility.

To evaluate the reasons for pit-latrines not being emptied, a more thorough investigation of all reasons was undertaken. Respondents were asked to provide one primary reason, which would be selected from a list of responses or which respondents could provide themselves. All responses from default responses were summed and unique responses were evaluated to identify their primary theme. Responses were initially grouped into subgroups based on similarities in the responses. Subgroups were then grouped into thematic groups, identifying three thematic areas: ‘lack of capacity’, ‘not appropriate for/ desired by the community’, and ‘not appropriate for the latrine’.

Table 6: Thematic groupings of reasons for pit-latrine rejection given in the national survey of latrine facilities. Responses are grouped by three thematic groups and broken into 12 sub-groups.

Thematic group	Subgroup
Lack of **capacity**	Lack of money to pay service provider
	Lack of technical knowledge to empty latrine
	Someone else empties facility
	No materials
	No service provider
Not appropriate for the **latrine**	Latrine not yet full
	Latrine design inappropriate (structural design does not permit emptying)
	Temporary/ additional facility
Not appropriate for the **community**	Against cultural beliefs
	Dig new latrine/ enough land
	No interest
Ambiguous	Ambiguous

Results

Spatial distribution of pit-latrine emptying

Figure 2 shows the percent of pit-latrines practising pit-latrine emptying within each 0.1 degree (approximately 11km). The area with the highest percent of pit-latrines being emptied was within Blantyre with 37.3% of pit-latrines undergoing pit-latrine emptying. On average, 1.26% of pit-latrines were emptied (2,540 cases).

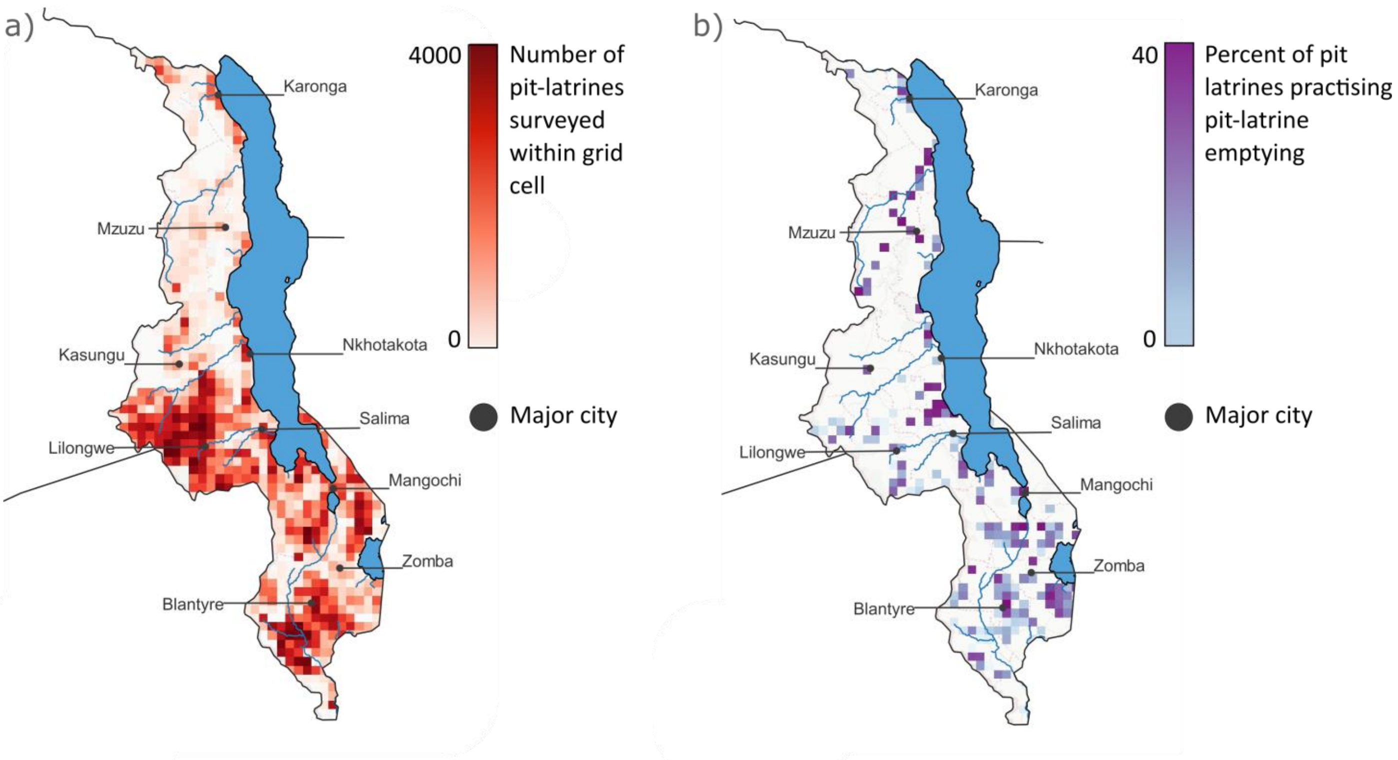

Figure 9: a) Pit-latrine sampling intensity, the number of pit-latrines sampled within each 10km grid cell. Maps produced in QGIS with voyager light background b) Intensity of pit-latrine emptying given as percentage of pit-latrines within a 10km cell practicing pit-latrine emptying. The highest levels of pit-latrine emptying practice were recorded around the cities of Blantyre and Mzuzu.

Pit-latrine emptying practices

The nature of pit-latrine emptying for the 2,540 pit-latrines undergoing emptying is summarised in Figure 3. Local service providers were the most common facilitators of pit-latrine emptying (56.1%). Manual emptying was the most common method used for emptying (80.2%) and the most common latrine emptying frequency was less frequently than every 3 years. The most common price for emptying was over 20,000 MK (2019). The averages of pit-latrine emptying frequency and cost are summarised in Table 1.

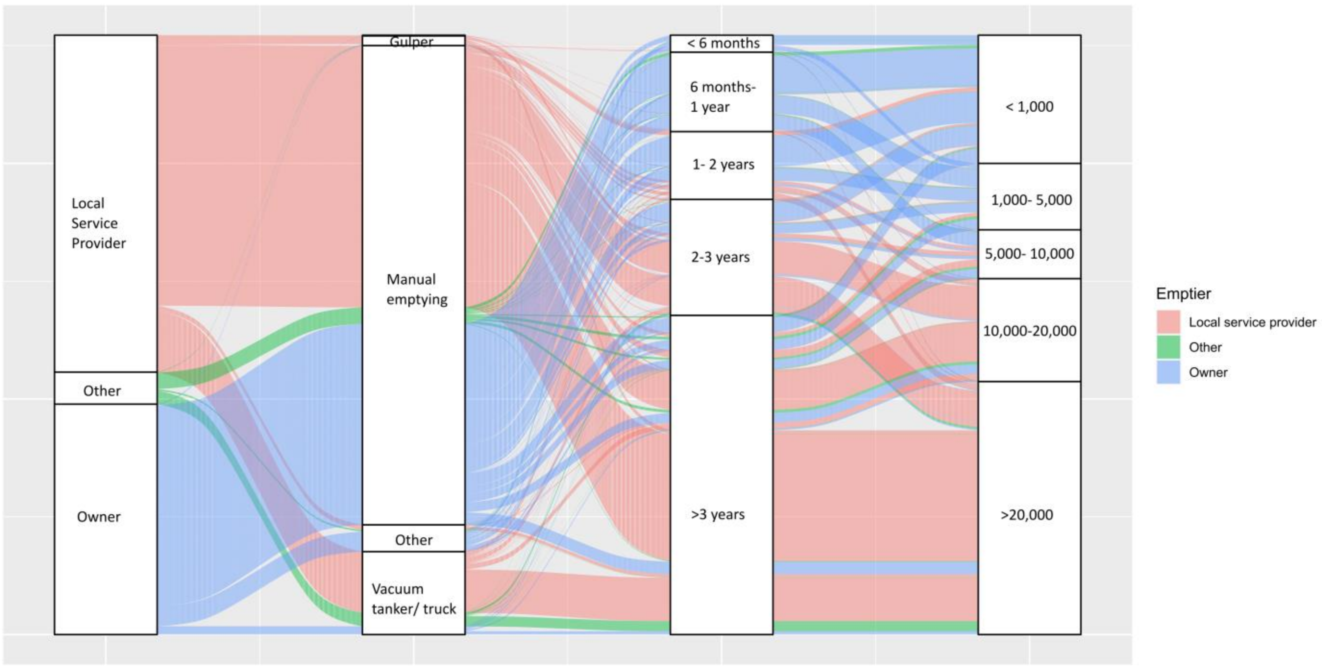

Figure 10: Pit-latrine emptying practices of facilities practicing pit-latrine emptying. Emptying provider, method, frequency and cost are summarized.

Table 7: Pit-latrine emptying practices summarizing average costs and frequency of emptying practices by pit-latrine emptying provider.

	Emptying cost/MK (2019)	Frequency/ years	Percent of pit-latrines emptied by provider %
All emptying	**15,280 ± 260**	**5.57± 0.07**	
Owner	6,560 ± 280	3.34 ± 0.11	38.6
Local service provider	21,070 ± 330	6.98 ± 0.08	56.1
Other	16,410 ± 1100	6.51 ± 0.32	5.32

Latrines emptied by owners were emptied more frequently than latrines emptied by local service providers (p-value < 2.2 x 10^{-16}), emptying an average of 2x as frequently. Latrine emptying by owners was cheaper (p-value < 2.2 x 10^{-16}), costing 3.2 x less than by local service providers.

Latrine replacement costs and risk of collapse

201,381 facilities had information on the type of facility and nature of construction. The average pit-latrine construction costs for average, lined, and unlined latrines as well as the structural condition of surveyed facilities is summarised in table 2.

Table 8: Pit-latrine construction cost, percent of collapse, and average age of the facilities by the type of construction.

	Latrine construction cost/ MK (2019)	Percent of latrines collapsed/ partially collapsed	Percent of latrines collapsed/ partially collapsed and not used	Average age of facility at time of survey
All latrines	**16,600 ± 40**	**19.5**	**4.38**	**3.81 ± 0.01**
Lined latrines	44,800 ± 160	7.04	0.18	6.53 ± 0.04
Unlined latrines	11,700 ± 30	21.6	5.11	3.23 ± 0.01
Pit-latrine without slab	11,000 ± 20	21.4	4.6	3.18 ± 0.01
Ventilated Improved Pit-latrine (VIP) *	64,600 ± 280	4.14	1.43	8.98 ± 0.1
Pit-latrine with slab *	35,800 ± 150	12.4	3.47	6.00 ± 0.03
Lined pit-latrine with slab *	49,800 ± 200	6.41	0.18	7.06 ± 0.05
Unlined pit-latrine without slab	10,400 ± 20	21.9	4.88	3.13 + 0.01
All improved pit-latrines (*)	**39,600 ± 150**	**11.3**	**3.20**	**6.39 ± 0.03**

On average 19.5% of latrines were partially or totally collapsed. Collapsed latrines were constructed at cheaper costs than structurally stable facilities (p-value < 2.2×10^{-16}). VIP latrines were the least likely to collapse (4.14%) but were also the most expensive, almost 4 times more than the average latrine and made up only 2.5% of all surveyed latrines. Unlined pit-latrines without a slab made up 76.2% of all latrines, they were the most likely to collapse (21.9%) and the cheapest to construct. Pit-latrine lining significantly reduced the risk of collapse, with unlined latrines 3.1 times more likely to be partially or totally collapsed than unlined latrines (average 21.6% and 7.04% of latrines respectively). Pit-latrines without a slab were 1.7 times more likely to be partially or totally collapsed than pit-latrines with a slab (average 21.4% and 12.4% respectively). Aside from VIP latrines, pit-latrines that were lined and with a slab were the least likely to collapse (average 6.41% totally or partially collapsed) and were 3.4 times less likely to collapse than unlined pit-latrines without a slab and 3 times less likely to collapse than the average latrine. Lined pit-latrines with a slab were 27 times less likely to be partially collapsed and not used or totally collapsed than unlined latrines. But lined pit-latrines with slabs were also more expensive, costing 3 times more than the average latrine and 4.8 times more than unlined pit-latrines without slabs.

The age of latrines that were filled is used as an estimate of the time taken for the latrine to fill up. On average, filled latrines were 7.0 ± 0.01 years old. Lined latrines with slabs took significantly longer to fill than unlined latrines without a slab (average 9.0± 0.4 years and 5.5± 0.1 years respectively, p value <0.001). Emptied latrines were significantly older than non-emptied latrines when surveyed (average 7.9± 0.2 years and 3.7± 0.01 years respectively, p-value < 2.2x 10-16). The average age of a lined pit-latrine with a slab was 8.0± 0.2 years for latrines being emptied and 7.0 ± 0.2 years for a latrine not being emptied.

The age of collapsed latrines (totally collapsed or partially collapsed and not in use) was used to estimate the time taken for the latrine to collapse. On average, latrines that were partially collapsed and not used or totally collapsed were 4.8 ± 0.5 years old. Collapsed unlined latrines without a slab were built more recently than collapsed lined latrines with a slab (average age 4.1 ± 0.04 years and 7.7 ±1.2 years respectively, p-value < 0.01). Due to the small number of lined pit-latrines with a slab which were collapsed, the estimate for the frequency collapse of lined pit-latrines with a slab was not used in scenario calculations.

Content analysis reasons for abandonment
Further analysis of the balance between filling or abandonment, based on latrine type, was taken by evaluating reasons given for why latrines had been abandoned and were not used (9,500 latrines). In total, 6,560 pit-latrines without a slab provided a reason for why they had been abandoned, 91.2% listed collapse due to rainfall or filling up as primary reasons for abandonment. The reasons for abandonment of 1,130 pit-latrines with a slab were provided, 88.8% listed collapse due to rainfall or filling up as a primary reason for abandonment.

Table 3 summarises the number of cases in which collapse due to rainfall or filling up were cited as reasons for abandonment of pit-latrines with a slab and pit-latrines without a slab.

Table 9: Number of cases where collapse due to rainfall or filling up were given as a reason for why abandoned latrines had been abandoned by the type of pit-latrine facility.

	Collapse due to rainfall listed as reason for abandonment	Filling up listed as reason for abandonment
Pit-latrine with slab	401	603
Pit-latrine without slab	4,400	1,580

Latrine management costs
The pit-latrine management costs of Scenarios A, B, and C are summarised in table 5. Appendix table 2 provides more detailed information of the costs and frequencies of replacement.

Under Scenario A, over a 30-year period, we estimate that there would be an average of 1.8 pit-latrines abandoned due to filling and 5.0 abandoned due to collapse. Over 30 years, we estimate the need to construct an average of 6.7 latrines (excluding the ‘initial’ pit-latrine construction cost) with an average cost of 10,400 MK (2019) and costing a total of 69,700 MK (2019). On average we assume an annual cost of 2,320 MK (2019) in construction.

We assume that under Scenario B, 2.16 latrines would be required over the 30-year period to replace collapsed latrines. We assume the average lined latrine construction cost for each facility of 49,760 MK (2019), on average we estimate an annual cost of 3,590 MK (2019) for construction. Assuming an emptying frequency of 5.6 years and taking the average emptying cost of 15,300 MK (2019), we predict an average annual emptying cost of 2,190 MK (2019).

Under Scenario C, we estimate an average of 2.9 pit-latrines would be constructed over the 30 year period with an average lined latrine construction cost 49,800 MK (2019). We estimate an average annual cost of 4,850 MK (2019) for construction.

Table 10: Average costs in the three stakeholder informed pit-latrine management scenarios

Scenario	A 'Standard'	B 'Pit-latrine emptying'	C 'Lined latrines no emptying'
Initial construction cost/ MK (2019)	10,400 ± 20	49,800 ± 200	49,800 ± 200
Estimated number of latrines required over given 30-year period	6.7 (5.0 collapsed, 1.8 filled)	2.2 (all collapsed)	2.9 (0.8 collapsed, 2.1 filled)
Average latrine lifespan/ years	4.48	13.6	10.3
Average annual construction costs (excluding initial)/ MK (2019)	2,320 ± 4	3,590 ± 15	4,850 ± 20
Average annual emptying costs/ MK (2019)	0	2,190 ± 100	0
Average annual cost (excluding initial construction) / MK (2019)	2,320 ± 4	5,780 ± 110	4,850 ± 20

Reasons against pit-latrine emptying

Table 6 summarises the reasons given for why pit-latrine emptying was not being carried out. 231,331 individual responses for why latrines were not emptied were provided and analysed (some surveys have more than one reason and were listed as separate responses).

Table 11: Reasons given for why pit latrine emptying was not carried out grouped by thematic groups and broken into sub-groups

Thematic reason	Sub-group	Number of responses	Percent of responses/%
Lack of capacity (77.9%)	Lack of money to pay service provider	27,600	11.9
	Lack of technical knowledge to empty latrine	152,000	65.8
	Someone else is responsible for facility emptying	141	0.06
	No materials	46	0.0199
	No service provider	158	0.0683
Not appropriate for the latrine (4.38%)	Latrine not yet full	9,720	4.20
	Design of latrine (locally made or structural design that not permit emptying)	265	0.115
	Temporary or additional facility	148	0.640
Not appropriate to/ wanted by the community (17.4%)	Against cultural beliefs	28,800	12.44
	No interest	147	0.0635
	Dig new latrine/ enough land	11,200	4.84
Ambiguous (0.371%)		856	0.371

A lack of capacity was the biggest thematic reason for the pit-latrine not being emptied (77.9%) with a lack of technical knowledge listed as the primary subgroup (65.8% of all reasons given). The second most common sub-group within this thematic group was a lack of money to pay a service provider and was the second most common response across all categories with 11.9% of responses. ‘Cultural beliefs’ was the second most common subgroup (12.4% of all responses).

Discussion

The importance of safe sanitation provision is emphasised within SDG6, which lays out the aim of ensuring access to adequate and equitable sanitation and hygiene for all, specifically ensuring access to safely managed sanitation services (UN General Assembly, 2015). Progress towards safely managed sanitation lags well behind provision of basic sanitation (UNICEF & WHO, 2023). Within Malawi, despite widespread pit-latrine usage, improved sanitation provision is low, at around 23% (Hinton et al., 2023b). This is largely due to the substandard quality of many sanitary facilities, with most pit-latrines not being covered by an appropriate concrete slab and, as such, failing to meet standards or safely managed service provision (Hinton et al., 2023b). Not only is ensuring higher quality pit-latrine construction important to meet sustainable development targets, but appropriate construction also has important benefits in minimising both the high frequency of pit-latrine collapse (Namwebe et al., n.d.; Reed, 2014) and the groundwater contamination risk (Graham & Polizzotto, 2013.; Gwenzi et al., 2023; Masindi & Foteinis, 2021) specifically lined latrines with a slab. Through a national survey of 268,180 latrine facilities across Malawi, we find that lined pit-latrines with a slab were 3.4 times less likely to collapse than unlined pit-latrines without a slab; 6.4% of lined latrines with a slab were partially or totally collapsed when surveyed compared to 21.9% of unlined latrines without a slab. Estimates of pit-latrine collapse are supported by literature (Kouassi et al., 2023). Similarly, pit-latrines with a slab were much less likely to have been abandoned due to rainfall induced collapse than pit-latrines without a slab (1.8 times more pit-latrines without a slab were abandoned due to collapse than pit-latrines with a slab). These findings support the suggestion that pit-latrine construction quality has a significant role to play in longevity of sanitary facilities.

Yet despite the benefits of pit-latrine lining and slab construction, many pit-latrines do not meet these standards. Of the analysed subset of 201,782 pit-latrines, 8.2% had both a slab and lining whilst 76% were unlined and without a slab. Cost plays an important role in latrine construction standards (Banana et al., 2015; Kariuki, 2003), we find that lined pit-latrines with slabs cost 3 times more than the average pit-latrine and almost 5 times more than unlined pit-latrines without slabs. Finding ways to make high-quality pit-latrine construction economically viable will be important in ensuring improved sanitation provision.

Pit latrine emptying practice

Sanitation management practices can minimise some of the challenges of pit-latrine use. Pit-latrine emptying provides one method of reducing chemical and microbial groundwater contamination (Gwenzi et al., 2023), particularly in minimising nitrate leaching (Templeton et al., 2015). In addition to mitigating some concerns for groundwater pollution, pit-latrine emptying could provide an alternative to the frequent pit-latrine replacement witnessed in Malawi. Reducing the frequency of latrine replacement due to filling could potentially incentivise higher-quality, long-lasting sanitary facility construction. Aside from the potential benefits, pit-latrine emptying is often the only viable solution within densely populated areas where spatial constraints make the abandonment and new construction of pit-latrines simply not possible (Kariuki, 2003). Pit-latrine emptying is therefore an essential consideration within sanitation policy, particularly in areas of high population growth and urbanisation such as Malawi (NPC, 2021).

Adoption for pit-latrine emptying within Malawi is low (Chipeta et al., 2017; Rochelle et al., 2015). This has been partially attributed to a lack of community knowledge of the benefits of faecal sludge management and a lack of community engagement within projects (Rochelle et al., 2015; Strauss & Montangero, 2004). A lack of community knowledge has been found to hold back the adoption of other sustainable WaSH practices within Malawi (Hinton et al., 2021). In addition, cultural considerations have also been highlighted as central deciders in faecal sludge management technology adoption (Buxton & Reed, 2010; Olapeju et al., 2019). Beyond the community level, a lack of clear guidance and regulation on the emptying, transportation and management of faecal waste has been identified as a major barrier to pit-latrine emptying capacity within East Africa (Jayathilake et al., 2019; Nanyonjo et al., 2022). Not only does the lack of guidance result in highly variable prices (Jayathilake et al., 2019), but also the process of emptying poses a health concern due to the pathogenic nature of faecal sludge (Riordan, 2009; Thye et al., 2009), making insufficient regulation and guidance a public health concern. Limited infrastructure to enable emptying, both a lack of disposal sites as well as urban and road infrastructure being incompatible with tanker trucks, further hold back pit-latrine emptying.

We found overall low adoption of pit-latrine emptying practices across Malawi with 1.26% of surveyed pit-latrines being emptied nationally. Higher pit-latrine emptying was found along roads and in urban areas where there may be greater service provider provision alongside increased pressure on space, necessitating emptying over replacement (Kariuki, 2003). Of the pit-latrines being emptied, local service providers were the most common practitioners of emptying (emptying 56% of pit-latrines being emptied). The remaining latrines were mostly emptied by owners. Manual emptying was the most used method for emptying by local service providers, owners, and other practitioners; 80% of all emptied latrines were emptied manually. This finding agrees with global literature identifying manual emptying as the most common method of emptying within sub-Saharan Africa. The high level of manually emptied latrines raises health and wellbeing concerns for practitioners (Riordan, 2009b; Thye et al., 2009) as well as environmental contamination due to the common inappropriate disposal of manually emptied faecal waste (Capone et al., 2020).

There was significant variation in pit-latrine emptying frequency and costs with prices ranging from under 1,000 MK (2019) (approximate 2024 equivalent of US $1.65) to over 20,000 MK (2019) (2024 equivalent of US $33.04). Owner emptying was significantly cheaper than local service provider emptying, costing an average of 6,562 MK (2019) (2024 equivalent US $10.84) whilst local service provider emptying cost an average of 21066 MK (2019) (2024 equivalent US $34.80). However, owner emptying also had to be conducted twice as frequently (every 3.3 years for owner emptied latrines and every 7 years for local service provider emptied latrines). It is likely that owners were unable to fully empty the pits. Therefore, despite local-service provider emptying being over 3 times more expensive than owner emptying per incidence, overall, owner emptying is only 40% cheaper than local service provider emptying. These fall within the range of recent literature estimates of latrine emptying cost and frequency both within Malawi (Holm et al., 2018) and other low-income settings (Balasubramanya et al., 2017; Burt et al., 2019).

Pit-latrine management scenarios

The overall cost effectiveness of pit-latrine emptying was also evaluated, comparing pit-latrine emptying costs to pit-latrine construction costs. Three scenarios were proposed to evaluate the potential of pit-latrine emptying to promote higher quality latrine construction. Scenario A assumes a current 'standard' situation of pit-latrine replacement when latrines are filled or collapsed. Pit-latrines in this scenario are unlined and without a slab, representing the most common type of pit-latrine surveyed (76.2% of facilities). Pit-latrine pricing was based on the average pit-latrine construction cost of this facility of 10,400 MK (2019) (2024 equivalent US $17.14). Latrines were assumed to fill every 5.5 years and were assumed to collapse on average once every 4.1 years based on estimates from this latrine type. As a result, most facilities will collapse before they are filled. The ratio of 'collapse' to 'filling up' as reasons for abandonment was used to scale the number of estimated latrines that would be abandoned and new latrines constructed, estimating that, over a given 30-year period, 4.9 facilities would be abandoned due to collapse and 1.8 facilities would be abandoned due to filling up. Under this management strategy, we calculate an average annual cost of pit-latrine replacement of 2,320 MK (2019) (2024 equivalent US $3.84). Further verification was conducted by comparison of the estimated pit-latrine lifespan of latrine facilities under this management programme (4.5 years) and the average age of surveyed facilities. The average age of surveyed unlined pit-latrines with no slab was 3.1 years (Q1= 1.5 years, Q2= 4.0 years), falling within the expected range for this lifespan.

Scenario B assumes the promotion of pit-latrine emptying alongside improved pit-latrine construction. Pit-latrines were assumed to be lined and with a slab, classing as improved facilities and offering greater structural integrity. Latrine construction costs were significantly higher for the improved facility, costing an average of 49,800 MK (2019) (2024 equivalent US

$82.20), almost 5 times more than the average construction costs of unlined pit-latrines without a slab. However, the latrines were also more than 3 times less likely to collapse than unlined latrines without slabs, thereby reducing the replacement frequency of collapse to once every 13.6 years. The pit-latrines were assumed to be emptied at the average emptying frequency of once every 5.6 years, costing 15,300 MK (2019) (2024 equivalent US $25.25) each occasion. This scenario was more expensive than the 'default' Scenario A as the reduced frequency of collapse was insufficient to offset the increased construction costs and a high cost of pit-latrine emptying. The strategy had an average annual cost of 5780 MK (2019) (2024 equivalent US $9.55) with 3590 annual construction cost (2024 equivalent US $5.93) and 2190 MK (2019) annual pit-latrine emptying costs (2024 equivalent US $3.62). The average age of lined pit-latrines with slabs undergoing emptying was 8.0 years (Q1 =3.8 years, Q2=9.6 years) supporting the hypothesis that pit-latrine lining and higher quality construction resulted in increased pit-latrine lifespan.

Scenario C assumes the promotion of improved (lined and with a slab) pit-latrine construction but no pit-latrine emptying. Under this scenario the improved construction standard of the pit-latrines results in a reduced risk of collapse (over 3 times less likely) as well as a longer time taken for the pit-latrine to fill (9.0 years). Pit-latrines are assumed to be abandoned at a 11:4 ratio of 'filling' to 'collapse' with an estimated 0.8 latrines being abandoned due to collapse and 2.14 latrines being abandoned due to filling up over a given 30-year period. This results in an average pit-latrine lifespan of 10.3 years. The reduced frequency of collapse is insufficient to compensate for the increased construction cost making this more expensive than the default scenario A, with an annual average cost of 4,850 MK (2019) (2024 equivalent US $8.00). The increased frequency of replacement required due to filling, in comparison to scenario B, does not offset the high costs of pit-latrine emptying making this cheaper than pit-latrine emptying. We verify the lifespan estimation in comparison to the average age of lined pit-latrines with a slab that are not undergoing emptying as 7.0 years (Q1 = 2.62, 9.52). This supports our hypothesis that this scenario would have a higher lifespan for each facility than the standard scenario A but lower than when pit-latrine emptying is practised.

All scenarios estimated sanitation service costs of under the US $3 to $4/ month, the estimated upper limit of affordability of urban households in low-income areas (Banana et al., 2015). Whilst high quality pit-latrine construction scenarios (B and C) resulted in predictably higher overall costs than the default, low-quality and low-cost pit latrine construction scenario (A), the associated reduced risk of collapse and therefore reduced frequency of replacement of high-quality facilities made the average increase in cost of higher quality pit latrine provision significantly less than the difference in construction alone. Despite lined pit-latrines with slabs costing almost 5 times more than unlined pit-latrines without slabs, the reduced risk of collapse makes upgrading to higher quality facilities just over 2 times more expensive per year on average (Scenario C). Promotion of higher quality construction should emphasise the enhanced lifetime of the facility highlighting that this reduces the disparity in cost. Importantly, the national economic benefits of improved sanitation provision must also be emphasised in cost-benefit considerations of improved sanitation provision (Van Minh & Hung, 2011).

Overall, pit-latrine emptying and high-quality pit-latrine construction was more expensive than the ‘standard’ scenario of low-cost pit-latrine construction and frequent replacement. Pit-latrine emptying did extend the lifespan of emptied facilities, requiring the fewest pit-latrine replacements. Pit-latrine emptying did also reduce the costs associated with promoting high quality pit-latrine *construction* by reducing the necessary frequency of replacement; annual average construction costs for high-quality facilities were 1260 MK (2019) (US $2.08 current equivalent) less under pit-latrine emptying. However, the high cost of pit-latrine emptying, with an annual average cost of 2,190 MK (2019) (US $3.62 current equivalent), undercut any financial benefits of the pit-latrine emptying. We suggest that under these scenarios pit-latrine emptying in Malawi is currently only cost effective for the most expensive facilities. Nevertheless, if pit-latrine emptying services could be reduced in price (either through less expensive per incidence pricing or less frequent emptying), pit-latrine emptying could provide a way to minimise the costs of high-quality pit-latrine adoption. We suggest that, for this to be the case, current local service provider pricing would need to more than halve (from a current average pit-latrine emptying frequency of 7 years and cost of 21,100 MK (2019), US $34.80 current equivalent) to bring the annual average pit-latrine emptying cost to under US $2.00 current equivalent.

Reasons for rejection of pit-latrine emptying

Qualitative analysis supports the call for the promotion of affordable pit-latrine emptying services. Pit-latrine emptying costs were the third most cited reason for why pit-latrine emptying was not conducted (cited by 11.9% of respondents) suggesting that investment to reduce pit-latrine emptying costs could lead to an increase in adoption. This echoes literature finding cost to be prohibitive to pit-latrine emptying in Malawi (Holm et al., 2018) and Rwanda (Burt et al., 2019). Similarly, the most cited reason, a lack of technical knowledge for latrine emptying (65.8%) could be overcome by promotion of affordable pit-latrine emptying services enabling emptying without owners requiring technical capacity. Municipal pit-latrine emptying services could provide a method to promote pit-latrine emptying and incentivise high quality latrine usage. An example is seen in the eThekwini Municipality in KwaZulu-Natal, South Africa, in which municipal workers provide emptying services of VIP pit-latrines at no cost on a 5-year cycle (Beukes & Schmidt, 2022). Whilst costless emptying services may not be economically feasible, providing subsidies for emptying could incentivise increased pit-latrine emptying practice (Burt et al., 2019; Kariuki, 2003). Costing of pit-latrine emptying subsidies should consider the cost of inaction and current high financial burden of inadequate sanitation provision in Malawi; in 2012 poor sanitation was estimated to cost Malawi approximately 1.1% of GDP ($US 57 million) (WSP, 2012).

Similarly, developing latrine emptying solutions that have low enough capital cost to encourage private sector expansion of pit-latrine emptying services may drive down pit-latrine emptying costs (Kariuki, 2003). Promotion of a competitive private sector market in pit-latrine services, alongside management of sanitation disposal sites, was established in Dar es Salaam, Tanzania, causing pit-latrine emptying services to halve (Kariuki, 2003). If similar success could be seen in Malawi, latrine emptying could reduce the prices associated with high-quality pit-latrine construction.

Whilst promotion and regulation of affordable pit-latrine emptying services may provide a method to promote higher quality pit-latrine construction, socio-cultural limitations to emptying cannot be ignored (Buxton & Reed, 2010; Olapeju et al., 2019). Pit-latrine emptying being against cultural beliefs was the second most common reason for why pit-latrines were not emptied (12.4%). Cultural factors must be considered within the development of appropriate pit-latrine emptying policy and practice (Rochelle et al., 2015).

Study Limitations

This study presented a national level evaluation of pit-latrine emptying practices and the potential for pit-latrine emptying to improve sanitary facility construction quality. As such, there were limitations to the level of detail possible to gather for every latrine. Estimates of latrine construction costs as well as the cost and frequency of emptying were based on categories with the average of each category taken in the calculation of the overall average. The upper estimates for the highest category was based on literature estimates of the upper limit. There may not be a normal distribution of values within each category resulting in the potential for under or over estimation of averages for these values.

In addition, whilst different fill-up times were calculated for lined to unlined latrines, the latrine lining itself can result in very different fill up times (Reed, 2014). Similarly, the study assumes a continuous rate of pit-latrine emptying, however, facilities may require more frequent emptying over time, potentially underestimating pit-latrine emptying costs over longer time periods (Jenkins et al., 2015).

The scenarios here provide comparative costs between scenarios, accounting only for pit-latrine construction and emptying prices as the main costs. Maintenance, cleaning, and supplies are not factored into the estimated pricing as these are assumed to be equal under all scenarios. As such, these results should not be taken as absolute values of the estimated costs of sanitation provision. Finally, it should be noted that since the survey completion (2020), Malawi has undergone high levels of devaluation, therefore prices in Malawian Kwacha are not applicable to current costs. Prices are given in the equivalent value of current (2024) US dollars based on the 2019 value of the Malawian Kwacha. In addition, whilst three national-level scenarios are evaluated there is likely to be spatial heterogeneity in pit-latrine management and emptying with regional variation in pricing and usage patterns making some scenarios more or less likely in different regions.

Policy recommendations

We propose several policy recommendations considering our findings. Firstly, pit-latrine lining, and the use of concrete slabs, should be promoted if not mandated not only to meet the need for increased access to improved sanitation, but also to minimise the risk of pit-latrine collapse, a key reason for a return to open defecation (Hinton et al., *in review*; Mosler et al., 2018). Promotion of high-quality latrine construction should emphasise the increased lifespan and hygiene of such facilities. Financial support, including loans, should also be considered due to the higher capital costs of higher-quality latrine construction. These aspects should be emphasised in sanitation promotion initiatives, such as the widely used community led total sanitation (CLTS) strategy, focusing on safe and sustainable sanitation provision over basic provision (Kouassi et al., 2023).

Secondly, by reducing the frequency of pit-latrine replacement, pit-latrine emptying could provide a method to minimise the costs of high-quality pit-latrine construction, facilitating the move towards ‘a higher bar’ for sanitation provision. Further incentivisation and subsidy provision, coupled with closer regulation, will be needed to promote appropriate pit-latrine emptying. We suggest that investment should be made into facilitating appropriate emptying by providing policy and regulation for pit-latrine emptying as well as investing in pit-latrine emptying infrastructure such as disposal sites. In addition, facilitation, and promotion of safe and sustainable usage of faecal waste, such as for fertiliser or biochar production, could drive down the price of pit-latrine emptying (Midega, 2022).

Finally, recognition of the cultural considerations surrounding faecal waste management are imperative. Management strategies to manage the growing burden of faecal waste management in culturally appropriate ways will be essential. Ensuring culturally appropriate faecal waste management will involve community engagement in strategy design and implementation (Buxton & Reed, 2010; Olapeju et al., 2019).

Conclusions

Despite widespread pit-latrine usage in Malawi, few pit-latrines (1.3%) undergo emptying. The lack of emptying necessitates pit-latrine abandonment upon filling up, exacerbating the challenges of limited space for pit-latrine construction, particularly in urban areas, and groundwater contamination. The high cost of pit-latrine emptying, with typical emptying costs similar to pit-latrine replacement costs, makes pit-latrine emptying economically unfavourable for most pit-latrine users. However, calls for increased pit-latrine construction standards with associated higher costs, raise the potential for pit-latrine emptying as a method to reduce the increased costs of high-quality pit-latrine construction.

We explore three stakeholder informed scenarios of pit-latrine construction and management, evaluating the costs of improved sanitation access. We find that higher quality (lined and with a slab) pit-latrines were three times less likely to collapse than the most common pit-latrines (unlined and without a slab). The reduced risk of collapse makes high quality pit-latrine usage more affordable than capital costs imply, with the increased lifespan of high-quality facilities making lined pit latrine with slab usage 2 times more expensive than unlined pit-latrines without slabs, this is despite the five-fold increase in capital costs of higher quality pit-latrine construction. Pit-latrine emptying could provide a system to subsidise the increased cost of higher quality pit-latrine construction further by reducing the frequency of pit-latrine filling, with higher quality facilities annually costing only 50% more than low quality facilities if pit-latrine emptying were offered for free. Current pit-latrine emptying costs are prohibitive with charges exceeding the savings from a reduced frequency of pit-latrine replacement. Increased regulation and appropriate promotion of pit-latrine emptying services could effectively bring down the price of emptying, enabling reduced pit-latrine abandonment, lower pit-latrine density, and a way to 'raise the bar' on the quality of sanitation provision.

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Consent

Informed consent was obtained from all subjects involved in the study. All data collected was in line with the Government of Malawi ethics and was agreed with each participant.

Data availability

Confidential data were provided by the Government of Malawi. All data summarised is provided here.

Conflict of Interest

The authors have no competing interests to declare.

Abbreviations

MK (Malawian Kwacha)

CLTS (Community Led Total Sanitation)

WaSH (Water Sanitation and Hygiene)

USD (US Dollar)

VIP (Ventilated Improved Pit-latrine)

Appendix

Appendix Table 1: Structural status of pit-latrine by the construction type.

	Number of latrines totally collapsed/ partially collapsed	Number of latrines totally collapsed/ partially collapsed and not used	Number of latrines structurally stable
All latrines	39,178	8,813	162,154
Lined latrines	2,090	55	27,643
Unlined latrines	37,088	8,758	134,369
Pit-latrine without slab	34,574	7,505	127,208
Ventilated Improved Pit-latrine (VIP) *	208	72	4,818
Pit-latrine with slab *	4,080	1,140	28,780
Lined pit-latrine with slab *	1,056	30	15,430
Unlined pit-latrine without slab	33,686	7,485	119,815
All improved pit-latrines (*)	4,288	1212	33,598

Appendix Table 2: Costs, frequencies of abandonment, and pit-latrine emptying variables of pit-latrines used in scenarios A-C

Scenario	A	B	C
Type of pit-latrine	Unlined pit-latrines without slab	Lined pit-latrine with slab	Lined pit-latrine with slab
Cost of construction	10,375 MK (2019)	49,760 MK (2019)	49,760 MK (2019)
Time to collapse	4.1 years	13.9 years	13.9 years
Time to fill	5.5 years	NA	9 years
Ratio of frequency of abandonment from collapse from rainfall to abandonment from filling up	14:5	NA	11:4
Cost of emptying	NA	15,300 MK (2019)	NA
Frequency of emptying	NA	5.6 years	NA
Years of accumulated waste in pit-latrines emptied		2.8 years	NA

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7.3.1 Postface

This piece answered RQ4 by meeting SO12 and giving the example of pit-latrine emptying. Pit-latrine emptying and lining offer two methods to minimise the risk of groundwater contamination from pit-latrines (as discussed in Chapter 5), providing solutions implemented by pit-latrine users to minimise the risk of contamination. In addition to the benefits for water quality, lining and emptying extend pit-latrine lifespan (by minimising the risk of pit-latrine collapse and preventing filling of pit-latrines). Extending pit-latrine lifespans reduces the frequency of pit-latrine abandonment, minimising the loss of sanitation infrastructure which can result in a return to open defecation (as discussed in Chapter 6). Yet, as in the case of borehole-garden permaculture, pit-latrine lining and emptying are uncommon with financial barriers presenting a major limitation to their adoption. This paper proposed that a reduction of the cost in pit-latrine emptying could develop a system to bring high-quality, lined, latrine construction in line with current pit-latrine costs providing a local solution to major challenges in sanitation and water access and progress to SDG6.

7.4 Conclusion to this chapter

Here, two local solutions that provide methods to address large-scale challenges in water and sanitation were discussed; borehole-garden permaculture was presented as a solution to high borehole non functionality and growing water scarcity whilst pit-latrine emptying was presented to tackle groundwater contamination and frequent loss of sanitation infrastructure. Despite their potential benefits, adoption for both practices is low with approximately 2% of water-points adopting borehole-garden permaculture and 1% of pit-latrines undergoing pit-latrine emptying. Tackling barriers to community engagement in solutions to water and sanitation challenges is critical not only to provide solutions to challenges in water and sanitation but also to directly address the call of SDG6.b in ensuring community engagement in such challenges.

The capacity for local level solutions to address multiple facets of challenges in water and sanitation was another area highlighted within this chapter with both cases addressing multiple threats to SDG6 alongside providing implications for other SDGs. Developing a holistic approach to understanding of SDG6 aids in identifying synergistic solutions challenges in reaching SDG6.

7.4.1 SDG6 targets explored in this chapter

This chapter primarily focused on SDG6.b which aims to 'support and strengthen the participation of local communities in improving water and sanitation'. The two community-led solution examples discussed address other targets within SDG6, namely, borehole-garden permaculture relates to SDG6.1 'safe drinking water for all' and SDG6.4 'water scarcity and water-use efficiency'. Pit-latrine emptying addresses SDG6.2 'sanitation and hygiene and end open defecation' as well as relating to SDG6.3 'water quality and wastewater'. The multiple targets explored in the chapter are shown in Figure 7.1.

Figure 7.1: SDG6 targets addressed in this chapter. This chapter primaruly focuses on SDG6.b, community participiation, but touches on many other aspects in demonstrating how local solutions can improve progress to SDG6

Chapter 8: Discussion

A holistic approach to SDG6

"Today's problems were yesterday's solutions."

Peter Senge, 1990

Chapter 8: Discussion. A holistic approach to SDG6

8.1 Introduction

Sustainable Development Goal 6 is not only critical to meeting the fundamental human rights of sanitation and water (OHCHR and UN-Habitat, 2010) but also intersects with multiple other sustainable development goals; it is essential for the elimination of poverty and hunger, and promotion of good health and well-being, education, gender equality, and many others (Pedersen et al., 2023). Connectivity between goals can be seen not only in SDG6s' significance to achieving multiple SDGs but can also be seen in synergies between targets making up SDG6 itself.

Within Malawi, water and sanitation challenges are particularly pertinent. Inadequate access to water and sanitation places a heavy burden on health, representing 52% of the national disease burden (UNICEF, 2021). Inadequate sanitation also presents a concern for reducing inequality with the burden of poor sanitation and hygiene falling disproportionately on women and girls; women and girls are responsible for fetching water in 7 in 10 households whilst also facing high burdens from inadequate safety and security in accessing sanitation (WHO/UNICEF, 2023).

Groundwater is central to water resources and the achievement of reaching SDG6 in Malawi, as it provides water for over 80% of the population (Graham & Polizzotto, 2013) this is accessed primarily from boreholes and tubewells which constitute 64% of the improved sources of drinking water(National Statistical Office, 2021). Challenges persist to Malawi's water resources within quantity, quality, and access. Over 10% of boreholes experience water shortages for at least one month of the year representing a challenge of water quantity whilst over 40% of boreholes are partially of completely non-functional, representing a challenge of water access (Kalin et al., 2019). Alongside issues of accessing sufficient water, challenges in water quality are also prevalent within Malawi's water resources; over 60% of the population rely on drinking water sources contaminated with *E. coli* (NSO, 2021).

8.2 Holistically viewing SDG6 to address multiple barriers

Meeting SDG6 'clean water and sanitation' for all requires addressing multiple barriers to ensure success. The need to simultaneously work to multiple targets and goals is seen particularly clearly in the goals SDG6.1 and SDG6.2.

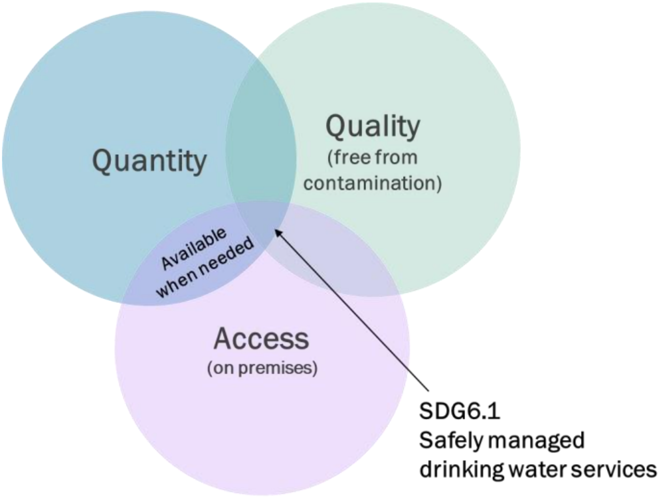


Figure 8.1: The intersection of quantity, quality, and accessibility in SDG6.1 'Universal and equitable access to safe and affordable drinking water for all'.

The provision of clean drinking water, as specified by SDG6.1, necessitates cooperatively addressing challenges to drinking water access, quantity, and quality (Grey and Sanoff, 2007). Progress to SDG6.1 is measured by the indicator SDG6.1.1 which evaluates "the proportion of the population using safely managed drinking water services", defined as "drinking water from an improved water source which is located on premises, available when needed and free from faecal and priority chemical contamination." (UN General Assembly, 2015). The intersection of multiple aspects of SDG6.1 is shown in Figure 8.1. Without ensuring all three aspects of clean water provision are met, the human right of access to water cannot be achieved.

This thesis has built on this philosophy, developing understanding of multiple challenges to water security within quantity, quality, and access. A stakeholder informed model of Malawi's groundwater resources developed insight into Malawi's diminishing groundwater supplies, emphasising a growing challenge of water quantity for ensuring clean water provision (Paper 2). The interconnection between Malawi's groundwater and surface water supplies further emphasised why groundwater must be a central consideration for Malawi's water security, not only recognising its central role in water supply but also that it underlies much of surface water security too (Paper 1). The significant challenge of groundwater contamination, and associated threats to water security was then explored, evaluating both microbial and nutrient contamination of groundwater resources. Sanitation infrastructure was identified as a major source of contamination of groundwater drinking water supplies (Paper 4) and the growing challenge of sanitation contamination from drinking water was emphasised (Paper 3). The challenge of borehole non-functionality and resulting limitations to water access was then emphasised, considering the local solution of borehole-garden permaculture in overcoming some of these challenges (Paper 8). In doing so this thesis developed a comprehensive overview of multiple aspects of water security (Grey and Sanoff, 2007) and multiple considerations of SDG6.1.

Similarly, within SDG6.2, which focuses on addressing sanitation and hygiene needs, multiple aspects of sanitation and hygiene must be simultaneously considered, with emphasis placed on both the 'proportion of the population using safely managed sanitation' *and* 'hand-washing facilities with soap and water'. Figure 8.2 summarises how SDG6.2 sits at the intersection of sanitation and hygiene provision. Even within the requirement for (safely managed) sanitation, there must be provision of both appropriate *access* (non-shared facilities) and *infrastructure* (appropriate excreta/ wastewater treatment). Within this thesis, multiple facets of appropriate sanitation and hygiene provision were considered to develop a holistic picture of Malawi's progress to SDG6. Malawi's progress to ending open defecation, and the challenges of population growth on this, were evaluated, identifying that, at current rates of progress, Malawi will not achieve SDG6 and end open defecation by 2030 (Paper 5). SDG6.2 specifies not only an end to open defecation but also access to *safely managed* sanitation, this was explored within the thesis. Currently improved facilities are only a quarter of sanitary facilities in Malawi, there is consequently a requirement of not only an increase in the *number* of sanitary facilities (increasing the rate of construction) but also *quality* of sanitary provision for Malawi to progress to SDG6.2 (Paper 5). Higher quality sanitary facility construction is also highlighted as an important consideration in ensuring *sustainable* progress to SDG6.2 and preventing a return to open defecation (Paper 6). Developing a holistic perspective of SDG6 recognises that progress within sanitation and water must be accompanied by improved hygiene provision.

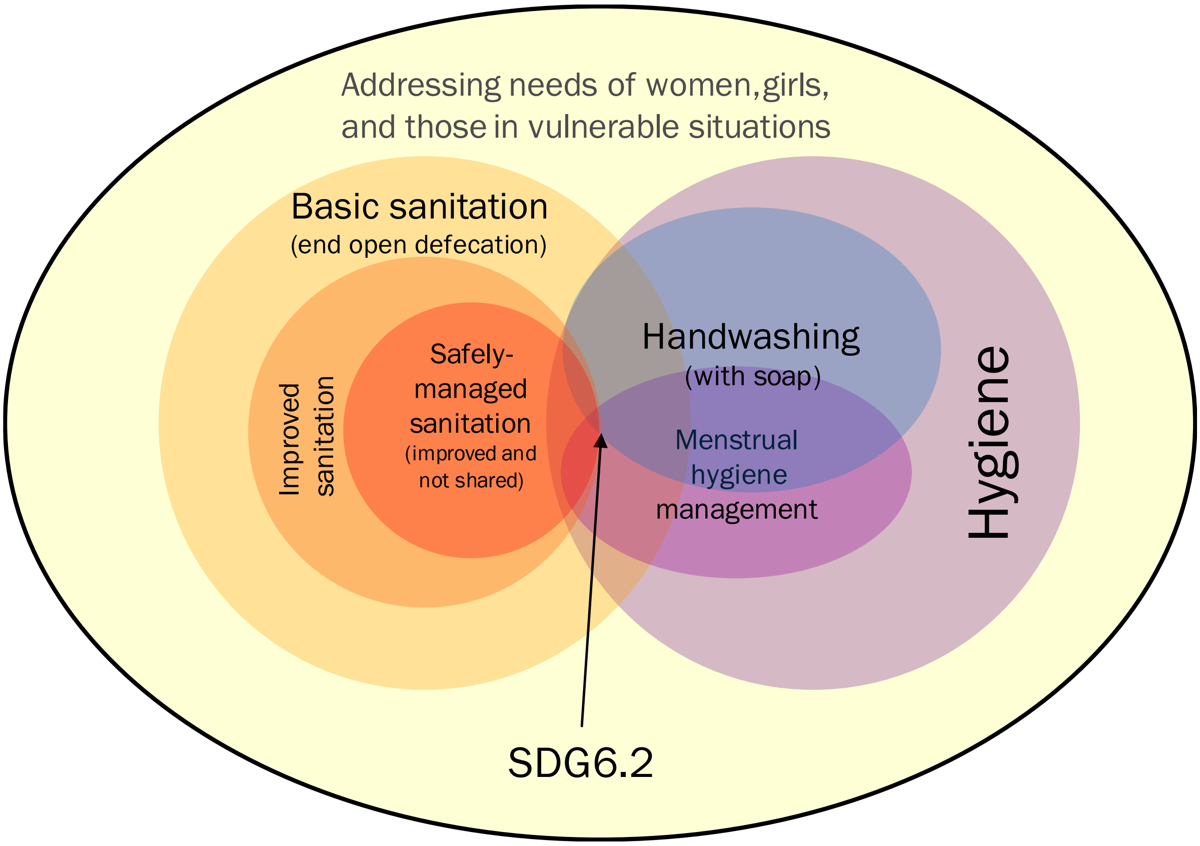


Figure 8.2: The requirement to consider multiple aspects of sanitation and hygiene within SDG6.2.

As in SDG6.2, this thesis has ensured that sanitation progress is considered in tandem with hygiene. To evaluate hygiene access, this thesis explored the prevalence of handwashing with soap, identifying soap use to be a major barrier to SDG6.2 and therefore limiting progress to SDG6 as whole (Paper 6). Figure 8.2 also represents how progress to sanitation and hygiene access must also meet the needs of 'women, girls, and those in vulnerable situations' in all aspects of sanitation and hygiene. Within this thesis, the needs of women and girls was specifically explored through evaluating privacy and security in sanitary provision, considerations that disproportionately impact women. The thesis identified that, even where sanitary facilities are provided, progress is frequently held back by the lack of provision of adequate privacy and, especially, security (Paper 6). In addition to consideration of handwashing, addressing the hygiene needs of women and girls necessitates consideration of menstrual hygiene challenges (Paper 7). This thesis explored multiple facets of SDG6.2 to build a more comprehensive overview of Malawi's progress within the sphere of sanitation and hygiene, considering multiple areas specified within SDG6.2 and SDG6 as a whole.

This multifaceted approach to considering Malawi's progress to SDG6 highlights this core concept that progress much be multilateral; unless progress is made towards all multiple aspects of SDG6 together, the associated benefits will be limited (Burnett et al., 2023; Naylor, 2023.). This is further highlighted in Figure 8.3 which depicts how the health and wellbeing benefits of improved in sanitation and water infrastructure are limited if there is insufficient improvement in hygiene and behaviour change. The focus on a cohesive effort to mutually reach all aspects of SDG6 echoes the ethos of the sustainable development goals themselves that the goals must be worked to 'hand-in-hand' (United Nations, 2024a).

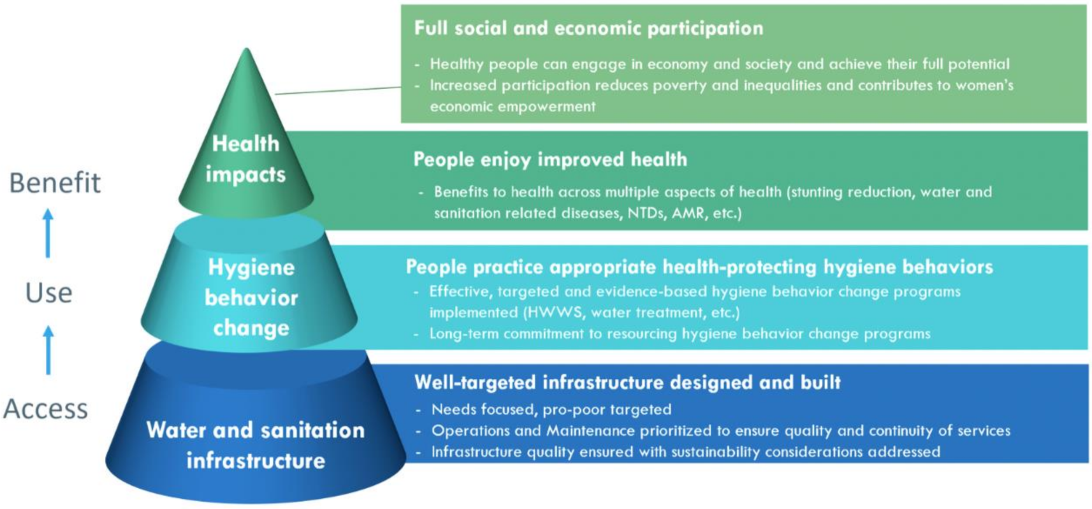


Figure 8.3. Foundational role of water and sanitation infrastructure in improving public health. Although water and sanitation infrastructure is necessary, in order to achieve the desired improvements in public health, hygiene behaviour changes are necessary in conjunction. Diagram by Bronwyn Powell (Powell and Fernandez-Illescas, 2021).

8.3 Holistically viewing SDG6 to identify conflicts

Not only is taking a holistic view of SDG6 necessary to ensure progress, recognising the cohesive nature of the targets within SDG6.2, viewing SDG6 holistically can aid in identifying potential conflicts within SDG6.

One of the clearest examples of conflicts between targets within SDG6 (intra-goal conflicts) can be seen in the case of sanitation contamination of drinking water supplies. Through a multi-method analysis of contamination of groundwater sources used for drinking water, this thesis identified that sources linked to sanitation currently present the most significant hazard to the quality of groundwater used for drinking (Paper 4). Projections based on current trends in sanitation and population growth suggest a growing challenge of water contamination as further sanitation development is required to keep pace with population growth and the goal of ending open defecation outlined in SDG6.2. Under current population growth projections and sanitation policy scenarios, there would be a a three-fold rise in water points vulnerable to contamination from pit latrines over the next 50 years (Paper 3).

This presents a paradox in progress to SDG6; sustained sanitation development is necessary to meet SDG6.2 and end open defecation, however, such proliferation of sanitary infrastructure, typically as pit-latrines, creates a risk for water quality and the achieving SDG6.1 and SDG6.3.

The example of sanitation contamination of water and internal conflicts within SDG6 creates another critical message of this thesis; without approaching SDG6 holistically, progress towards one target may come at the cost of other facets of SDG6. To mitigate against conflicts within SDG6, the development and implementation of effective policies relating to sanitation and water must occur concurrently.

8.4 Holistically viewing SDG6 to provide synergies

Not only does a holistic view of SDG6 help to avoid conflicts between targets, taking a holistic approach can also identify areas of synergy within targets comprising SDG6. One area in which this can be seen in the case-study of coupled pit-latrine emptying and high-quality sanitation infrastructure construction. When not properly maintained, pit-latrines pose risks of groundwater contamination due to leaching of pollutants from human waste into the surrounding soil and groundwater. This contamination jeopardizes water quality, potentially leading to the spread of waterborne diseases and affecting public health (Papers 3 and 4). Additionally, inadequate maintenance of pit latrines can result in their collapse or filling up, leading to the loss of sanitation infrastructure and possibly a return to open defecation, further exacerbating sanitation challenges (Papers 5 and 6). Pit-latrine emptying, and high-quality facility construction can be used to minimise both challenges, simultaneously reducing contamination of groundwater and collapse (Paper 9). In doing so, coupled pit-latrine emptying and high-quality construction is an example of a solution with synergies in progress toward SDG6, simultaneously addressing challenges related to both water quality and sanitation. This is an example of an intra-goal synergy (Bongolan et al., 2022).

Taking a holistic view of SDG6 not only involves to identifing intra-goal synergies but also considers inter-goal synergies (Bongolan et al., 2022); the interaction of SDG6 with areas of the SDGs, such as health, poverty alleviation, gender equality, and environmental sustainability; inter-goal synergies. For example, interventions that improve access to clean water and sanitation can have positive impacts on health outcomes, economic productivity, educational attainment, and environmental conservation (Kroll et al., 2019). Identifying these synergies allows for the development of integrated and multi-sectoral approaches that maximise benefits across various dimensions of sustainable development, ultimately accelerating progress toward achieving the broader agenda of sustainable development (Kroll et al., 2019).

An example of inter-goal synergies in the SDGs is characterised in this thesis is borehole-garden permaculture which highlights how consideration of working towards SDG6 can contribute to multiple SDGs beyond SDG6 (Paper 8). By utilising waste water from boreholes to irrigate a community-managed garden nutritious crops can be grown year-round promoting food security and sustainable agriculture practices aligned with SDG2 ‘zero-hunger’. Improved access to fresh produce enhances nutrition and dietary diversity, leading to better health outcomes, supporting SDG3's goal of good health and well-being. Additionally, borehole garden permaculture embodies climate-resilient agricultural practices, contributing to climate change adaptation and mitigation efforts outlined in SDG13. Implementing borehole garden permaculture also fosters inclusive and participatory partnerships to sustainable development as envisioned in SDG17. In summary, the example of borehole garden permaculture discussed in this thesis exemplifies the interconnectivity of sustainable development efforts and the potential for holistic solutions to address complex challenges across multiple SDGs.

8.5 Conclusion to this chapter

This chapter explored how a holistic perspective of the multifaceted challenges and interconnected goals within SDG6 can be used to address multiple barriers, identify challenges, and provide synergistic solutions in progressing to SDG6. Examples of challenges and solutions in water and sanitation in Malawi from within this thesis are discussed to provide clear cases of how a holistic view of SDG6 can enhance progress.

The chapter emphasised the need for a holistic approach to address the multiple barriers to achieving SDG6, particularly highlighting the interconnectedness of targets within SDG6.1 and SDG6.2, which focus on clean drinking water provision and sanitation access, respectively. It explored the necessity of addressing challenges related to water quantity, quality, and access simultaneously to ensure the fulfilment of the human right to water. The chapter also discussed the importance of intra-goal conflicts within SDG6, using the example of contamination of drinking water sources from pit-latrines. The chapter emphasised the need for concurrent development and implementation of effective policies regarding water and sanitation. Finally, the chapter explored intra and inter-goal synergies of SDG6, exemplified by examples of locally managed solutions of borehole garden permaculture and pit-latrine emptying.

Overall, this chapter underscored the importance of a holistic perspective on SDG6 to effectively address complex water and sanitation challenges and advance broader sustainable development objectives in Malawi and beyond. Developing a holistic perspective as explored within this chapter necessitates breaking down traditional silos within research, policy, and funding structures. By breaking down these silos and fostering interdisciplinary collaboration, researchers, policymakers, and funders can better identify synergistic opportunities that cut across different sectors and goals both within SDG6 targets and between SDGs. This approach allows for the development of integrated strategies and solutions that maximize impact and efficiency, ultimately advancing progress toward achieving broader sustainable development objectives.

Chapter 9: Conclusions and recommendations

"I realised that the purpose of writing is to inflate weak ideas, obsucure reasoning, and inhibit clarity. With a little practice writing can be intimindating and impenetrable fog!

Academia here I come!"

"Calvin and Hobbes". Bill Waterson, 1994

Chapter 9: Conclusions and recommendations

9.1 Introduction

This thesis aimed to develop understanding holistic understanding of both challenges and solutions to meeting SDG6 in Malawi. Multiple perspectives of SDG6 have been examined through considering challenges and solutions, national and local levels, and examining water and sanitation.

The work presented was motivated by an appreciation of the highly interconnected nature of water and sanitation to achieve SDG6 while recognising the largely siloed streams of water and sanitation policy. The thesis was directly driven by stakeholder concerns surrounding meeting SDG6 within multiple aspects of water management (particularly water quantity and quality), sanitation, and hygiene. Limited data and a lack of consensus surrounding both sanitation and water (notably groundwater) made assessing these areas challenging. This thesis consequently developed novel methods to explore sanitation and water resources, providing insight into current and future barriers to SDG6.

To ensure a holistic perspective and address the often-dismissed aspect of SDG6.B, ensuring local participation in water, sanitation, and hygiene, the thesis finally explored local level solutions to some of the national challenges in water and sanitation identified. Maintaining a holistic view of SDG6 mirrors the interconnected ethos of the Sustainable Development Goals themselves.

Specifically, the thesis addressed 4 research questions, with associated specific objectives. The overall conclusions and ways in which each research question has been met through the thesis are detailed below. Specific policy objectives and recommendations for future research follow.

9.2 Summary of key findings

Chapter 4 focused on RQ 1, 'What are challenges to water scarcity in Malawi?' by identifying the connection between surface water and groundwater in Malawi's largest surface water resource, Lake Malawi. Developing understanding of the role of groundwater to Lake Malawi surface water storage met SO1 and emphasised the centrality of groundwater in water scarcity challenges (SDG6.4) in Malawi. Chapter 4 emphasised that, despite its significance, there is limited understanding of Malawi's groundwater supplies owing largely to an insufficient groundwater monitoring network, novel methods are therefore needed to understand groundwater in Malawi and meet RQ1 in understanding water scarcity within Malawi. To meet this need of greater groundwater understanding to address RQ1, given the results of SO1, the chapter met SO2 by developing a model of groundwater availability within the Lake Malawi Shire River Basin.

The chapter demonstrated that current global hydrological models (taking the Community Water Model, CWatM), do not adequately perform to provide insight into water resources in Malawi. Chapter 4 therefore achieved SO2 of RQ1 by modifying the CWatM to develop a stakeholder-informed model of Malawi's groundwater resources that performed better than the previously available model. SO2 responded to RQ1 by developing understanding of current groundwater resources to inform understanding of water scarcity.

Finally, Chapter 4 answered RQ1 by applying SO3 and identifying a consistent decline in groundwater resources in Malawi from 1970, emphasising the risks to groundwater security and water scarcity. The work enabled the first national estimates of groundwater resources and provided the first evidence of a sustained, national decline in groundwater table. Taking the earlier results (from SO1) of the implications of groundwater for surface water, this chapter painted a worrying trend for water scarcity in Malawi due to declining groundwater levels not only reducing the vital water resource of groundwater but also threatening Malawi's surface water resources. *Malawi's water security (absence of scarcity) is dependent on groundwater, but groundwater security is under threat.*

Chapter 5 addressed another component of ensuring water security and meeting SDG6, water quality by addressing RQ 2 “What are challenges to water quality in Malawi?”. The chapter focused on groundwater due to its central role in water security and meeting SDG6, as highlighted in Chapter 4. The chapter focused on the case of faecal contamination of groundwater resources due to the high burden of *E coli* contamination of groundwater drinking water sources. Specifically, the chapter achieved SO4 to address RQ2 and evaluate faecal groundwater contamination. The chapter achieved SO4 using large datasets of pit-latrine usage to develop a novel method to predict pit-latrine density from gridded population distributions. Predicted pit-latrine density was verified with measured pit-latrine density with high accuracy. Analysis of data of over 100,000 water-points across Malawi predicted that 11.5% of water-points were at risk of groundwater drinking water contamination, the model developed predicted this to be 15%, showing good accuracy at identifying water-points at risk of contamination. Through the development of a system to predict pit-latrine density and associated groundwater water-point risk from gridded population distribution, the model was applied to future population scenarios to respond to SO5. The chapter achieved SO5 through predicting future groundwater contamination risks from pit-latrines to water-points under 5 scenarios of population growth (modelled on the 5 SSPs) and 3 scenarios of sanitation policy. The chapter identified a growing challenge of pit-latrine contamination of water supplies to address SO5.

The chapter finally achieved SO6 to directly link the modelled pit-latrine density generated in SO4 and SO5 to drinking water quality. The chapter used the model of pit-latrine density developed in SO4 to achieve SO5 and identify the drivers of groundwater drinking water supply contamination. The chapter identified high pit-latrine density as the most significant driver of high *E. coli* contamination and catchment level pit-latrine use as the most significant driver of nitrate contamination of groundwater drinking water supplies. The chapter revealed that ensuring water quality within Malawi, and SDG6, necessitates considerations of sanitation infrastructure within drinking water management. The chapter directly responded to RQ2 by identifying pit-latrine contamination of groundwater as the major challenge to water quality for reaching SDG6 and a growing challenge going forward. *Malawi's water quality is under threat from inappropriate sanitation infrastructure.*

Chapter 5 highlighted how sanitation must be considered within preserving Malawi's water quality, ensuring water security, and ultimately meeting SDG6. However, there is a large amount of uncertainty surrounding Malawi's sanitation infrastructure. Not only is more understanding of Malawi's sanitation needed to better understand water quality (as addressed by Chapter 5), understanding sanitation and hygiene is also essential for meeting SDG6.2, a core component of SDG6.

Chapter 6 responded to the need for greater understanding of sanitation and hygiene to meet SDG6. Chapter 6 answered RQ3 'What are challenges to sanitation and hygiene provision in Malawi?'**.** Chapter 6 responded to the challenge of conflicting estimates of uncertainty in Malawi's sanitation provision by achieving SO7, analysing a large dataset of sanitation infrastructure to identify the current level of improved sanitation provision. It identified a major challenge of most sanitary facilities being unimproved facilities, thereby failing to meet requirements for SDG6.2. Comparing future scenarios of population growth with projected sanitary provision was used to achieve SO8, predicting future progress to ending open defecation. Completion of SO8 answered RQ3 by identifying the rate of sanitation development as a major challenge to meeting SDG6 in Malawi; evidencing that Malawi's current rate of sanitation provision is inadequate to meet the level of development required by the growing population. This chapter achieved SO9, exploring how communities previously declared 'open defecation free' evidenced a return to open defecation shortly after eliminating open defecation. SO9 answered RQ3 by identifying the challenge of slippage in progress and a reversal of sanitation provision as a challenge to sanitation provision. The chapter highlighted that pit-latrine collapse alongside filling of pit-latrines leads to a high level of pit-latrine abandonment representing a loss of infrastructure and investment in sanitation.

The chapter also addressed challenges in hygiene, recognising that without appropriate hygiene eliminating challenges in water security and sanitation provision will have limited benefit not only in reaching SDG6 but also improving environmental and public health. Chapter 6 addressed SO10 by exploring handwashing and menstrual hygiene management (MHM) as two cases of hygiene practice. This chapter identified behavioural barriers as major challenges to hygiene practice including insufficient prioritisation of soap for handwashing and cultural barriers to drying menstrual absorbents outside. By the identification of barriers to hygiene practice, SO10 directly answered RQ3. *Inadequate infrastructure and behavioural barriers present major challenges to sanitation and hygiene provision.*

Chapter 7 answered RQ4 by discussing two solutions to some of the challenges identified in RQs 1,2 and 3. The chapter focused on local solutions to address RQ4, in doing so responding to SDG6.b which highlights the importance of local level participation in sanitation and hygiene development. Through achieving SO11 and discussing the case of borehole-garden permaculture as a locally managed sustainable water use practice, the chapter answered RQ4 in relation to the water challenges of water scarcity and borehole-non functionality, mentioned earlier in the thesis. In doing so it identified a local solution to one of the challenges of unsustainable groundwater use and depleting groundwater resources (RQ1). The work suggested ways in which the adoption of the techniques can be improved to best respond to the challenges discussed by suggesting areas where borehole-garden permaculture can be utilised for maximal benefit, emphasising the importance of social capital in the promotion of sustainable techniques. The importance of considering water point committees as local agents of water management was emphasised in promoting local level solutions and addressing RQ4.

Chapter 7 achieved SO12, discussing pit-latrine emptying as a method to promote higher pit-latrine construction (including lined latrines). It directly responded to RQ4 by discussing how pit-latrine emptying can be used to provide a local solution to the dual challenges to water and sanitation of groundwater contamination from sanitation (RQ2) and pit-latrine abandonment from filling up and collapse (RQ3). The work provided evidence that higher-quality pit-latrines have longer lifespans and collapse less frequently but identified financial barriers in high-quality pit-latrine construction; on average, 'high-quality' lined pit-latrines with slabs cost 5 times more than the 'poor-quality' unlined pit-latrines without slabs (the most common facilities). Pit-latrine emptying could be used to make high-quality pit-latrine construction more affordable by reducing the frequency of replacement required by pit-latrine filling, however, current pit-latrine emptying costs are prohibitive, making this local level solution to water and sanitation challenges largely unachievable. The chapter addressed RQ4 by identifying solutions to the major water and sanitation challenges discussed at a local level, however also identifying significant barriers in their implementation. *Local level solutions to national level threats to water and sanitation exist, but are held back by multiple, largely socioeconomic, barriers.*

Not only has this thesis responded directly to the 4 research questions above, but it has also met the aim of developing a holistic overview of challenges and solutions to SDG6 through touching on every target within SDG6 to build a comprehensive overview of Malawi's path to SDG6. Although some targets within SDG6 have had greater focus (notably SDG6.1, SDG6.2, SDG6.3, SDG6.4, and SDG6.b) than others (particularly SDG6.5 and SDG6.6), the thesis has nonetheless developed a holistic conceptualisation, enabling areas of conflict and synergy to be identified. The entire thesis directly addressed SDG6.a though supporting the developing country of Malawi in water and sanitation development. Figure 9.1 demonstrates how every aspect of SDG6 has been considered within this thesis.

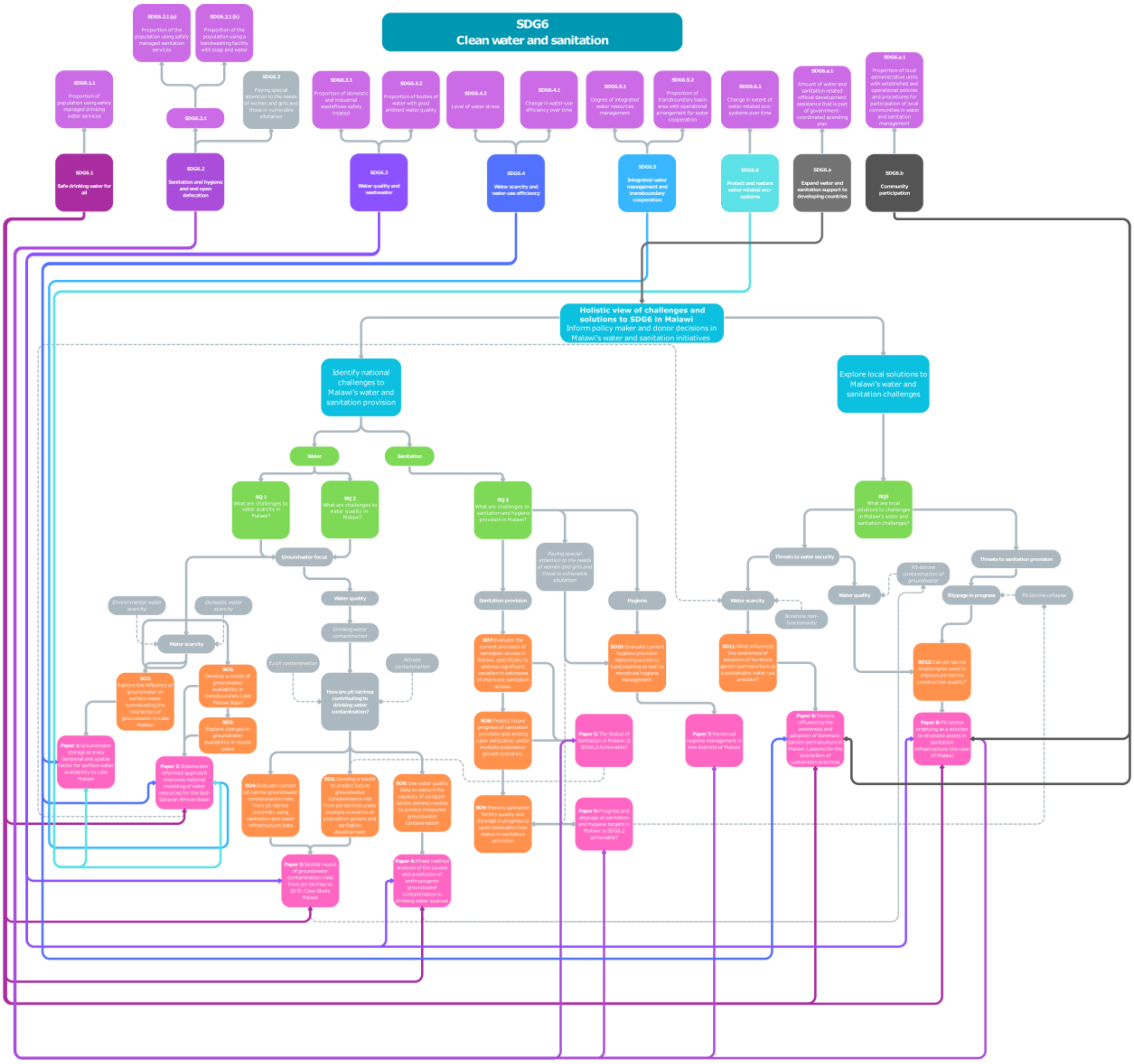


Figure 9.1: The ways in which every aspect of SDG6 has been considered within this thesis. The indicators within SDG6 are shown in puriple. Specific targets of SDG6 are shown at the top of the diagram with colours of connectors between areas of SDG6 and the papers forming parts of chapters in this thesis are given in the colour of the SDG6 target it relates to.

9.3 Contributions of this thesis

By directly addressing identified knowledge gaps and stakeholder concerns, this thesis has contributed to the international academic understanding of SDG6, not only through published peer-reviewed literature, but also through informing policy and Government of Malawi reports. Specifically, this thesis has contributed novel methods and enhanced understanding by:

- Developing understanding within the research gap of the role of groundwater in Lake Malawi's water resources.

- Responding to calls for greater groundwater understanding by developing the first system-modelled estimate of national groundwater resources in Malawi and provided the first estimates of national level groundwater storage change.

- Identifying key modifications to enhance hydrological modelling within the case-study of the LMSRB with implications for other Sub-Saharan African basins.

- Developing a new method for modelling pit-latrine risk to groundwater resources to evaluate current pit-latrine contamination alongside future risk under multiple scenarios of population change and sanitation policy.

- Increasing understanding of major causes of contamination of groundwater drinking resource in Malawi, identifying sanitation related causes of contamination as the major drivers of high *E. coli* and nitrate contamination.

- Developing understanding of Malawi's sanitation provision and prospects for ending open defecation, identifying challenges to achieving SDG6.2.

- Responding to a lack of understanding of the sustainability of the long-term sustainability of the elimination of open defecation, enhancing literature on the sustainability of improvements in sanitary provision under the internationally used CLTS framework.

- Enhancing understanding of household MHM in low-income setting, an understudied aspect of hygiene provision and SDG6.

- Improving understanding of local level sustainable water management adoption by communities through the example of borehole-garden permaculture.

- Providing the joint solution of pit-latrine emptying and lined pit-latrine construction to the dual issue of high pit-latrine abandonment and groundwater contamination seen in many low-income countries. Developed understanding of financial benefits and barriers to pit-latrine emptying and high-quality pit-latrine construction in Malawi.

-Contributing to dialogue on the reasons for holistic approaches to SDG6 in addressing multiple barriers, identifying conflicts, and finding synergies towards SDG6 (chapter 8) using the examples from this thesis.

9.4 Specific policy recommendations

This thesis was based on a foundation of stakeholder engagement and directly addressing stakeholder concerns. Each piece of work within the thesis directly responded to stakeholder needs through specific policy recommendations. However, one of the most significant policy recommendations when viewing the thesis as a collective is the importance of developing cooperation between sanitation and water policy to mitigate conflicts and to enhance potential synergies(Chowdhury et al., 2021; Sanitation and Water for All, 2021). This thesis has already identified some areas of conflict, notably sanitation contamination of groundwater, as well as synergy, such as high-quality sanitation construction to minimise contamination risks as well as prevent a return to open defecation. Malawi has already made bold steps in recognising the inherent interconnectivity of water and sanitation including developing the Ministry of Water and Sanitation launched in 2022 which contains the departments of Water Resources, Water Supply Services, as well as Sanitation and Hygiene. Prior to this, the Department of Water Resources was held within the Ministry of Forestry and Natural Resources whilst the Department of Sanitation and Hygiene was previously within the Ministry of Health.

Through bringing the department for sanitation and hygiene under 'one roof', the Government of Malawi is fostering the potential for greater synergy and a recognition of the interconnection between water, sanitation, and hygiene. The generation of a single Ministry and generation of a shared vision 'Water and Sanitation for all, always' greatly enhances collaboration through strengthening mutual accountability (Chowdhury et al., 2021; Sanitation and Water for All, 2021). However, further policy steps should be taken to generate effective synergy and prevent conflicts between these focus areas. One potential area of development is in the promotion of multidisciplinary teams and effective partnerships between policy makers in different departments through peer-peer partnerships and enhanced collaboration(Bravo, 2019; UNESCO, 2023). Expanding understanding of the inherent interconnectivity of challenges in water and sanitation also aids effective exchange, fostering productive collaboration. Creative methods of communication, such as the use of serious gaming (Appendix A) can be applied to enhance understanding of the interconnectivity within water, sanitation, and hygiene.

Specific areas of policy recommendation are also provided, these focus specifically on Malawi's progress to SDG6 but are applicable across global contexts.

9.4.1 Groundwater management policy

Consideration of groundwater security must be accounted for within any analysis of water security, including surface water. This was highlighted in Chapter 4 which evidenced the interconnection between groundwater and Lake Malawi water storage (Paper 1). Groundwater must therefore form a central part of water security dialogue.

Within Malawi, evaluations of future water scarcity should consider groundwater depletion as a major threat. Consistent and sustained depletion of groundwater within Malawi was underscored within Chapter 4 (Paper 2), raising a concern for the future of Malawi's groundwater resources. Sustainable groundwater use must be a priority and measures to prevent the overexploitation of groundwater need to be included within irrigation expansion plans (ERM, 2013; SAGCOT, 2024).

Policy should not only consider methods to reduce over extraction of groundwater, but steps should also be taken to promote safely managed groundwater recharge, this is underlined in that over 10% of water-points within Malawi currently experience seasonal non-functionality (Kalin et al., 2019).

9.4.2 Sanitation and Hygiene policy

Given the significance of sanitation infrastructure as sources of water contamination highlighted in Chapter 5, sanitation policy must consider the implications of sanitary infrastructure on groundwater quality. Alternatives to unlined pit-latrines should be promoted particularly in areas with a high density of pit-latrines and a heavy reliance on groundwater for drinking (Papers 3 and 4). Such alternatives may include the expansion of piped sanitation networks, where appropriate, or promoting pit-latrine lining and emptying (Paper 9). In addition to infrastructure development, enhanced monitoring, and dynamic assessment of risks from pit-latrine infrastructure will be important.

A shift is needed in the framing of sanitation development from a short-term focus on open defecation elimination (which is often short-lived due to the limitations of infrastructure provision and a rapidly growing population) to the promotion of high-quality, safely managed sanitation systems (Par 6). This may involve setting targets to districts to achieve given thresholds of safely managed sanitation access as an alternative to current targets of achieving ‘open defecation free’s status. This should not be seen simply as an alternative to eliminating open defecation but rather a strategy to promote sustainable progress in sanitation provision. The development of high-quality sanitation should also be recognised as having synergistic benefits for both sanitation and clean water provision (Paper 9).

Educational programmes to promote behavioural change within hygiene should be delivered in tandem with promotions of sanitation, in recognition that without effective hygiene improvements, the benefits of sanitary improvement are limited. Chapter 6 explored how, despite CLTS programmes within Malawi, handwashing with soap is still limited even in communities that had undergone CLTS programmes. Educational programmes should focus on the promotion of soap use in handwashing. Similarly, educational programmes should address appropriate MHM including the importance of appropriate menstrual absorbent drying which was identified as a particular concern (Paper 7).

9.4.3 Policy for community engagement in sanitation and water management

Local level participation must be a priority, not only in reaching SDG6 but also facilitating multiple local-level solutions to water and sanitation challenges, as emphasised by Chapter 7. Enhancing community adoption of sustainable techniques in sanitation and water should build on existing social capital. Their promotion should also focus on breaking down specific barriers to adoption, engaging communities in all stages of this process to identify limitations to their adoption (Papers 8 and 9).

9.5 Future research directions

Alongside the policy recommendations discussed in 9.4, this work also identifies several areas of future scientific research to enhance progress to SDG6.

9.5.1 Water scarcity

Improvements need to be made in modelling efforts to enhance understanding of water resources, particularly groundwater. These should be appropriate to the water management context of Malawi, applying stakeholder informed expertise to accurately represent water resource management. Enhancements to the appropriate modelling of Malawi's water resources have implications not only for Malawi's national water resources but also for modelling water resources in other SSA basins. Future modelling efforts should focus on the incorporation of future scenarios of climatic and societal change to enable better insight into long-term policy and resource management scenarios.

This thesis highlighted challenges of groundwater depletion on a national scale. Sustainable groundwater management should therefore be a priority for future research, investigating the potential for solutions such as managed aquifer recharge to enhance water security without resulting in undesired consequences, particularly for water quality.

A critical area of future research within Malawi is also in the consideration of borehole functionality to ensure water access alongside challenges of water scarcity. Further research into how communities can be empowered to ensure borehole-functionality, both developing innovative solutions and bolstering existing approaches, should be an area of focus.

9.5.2 Water contamination

This thesis highlighted the concern of groundwater contamination from sanitation infrastructure (notably pit-latrines), highlighting the concerns for environmental and public health. However, despite the significance of pit-latrines, as potential point-sources of contamination, there is limited capacity to identify and thereby manage contamination from pit-latrine sources. Current methods to identify pit-latrines, largely through surveys or visual inspection (Hinton et al., 2023; Martínez-Santos et al., 2017, Oyunbat et al., 2022, Van den Homberg et al., 2020), are time and cost intensive, limiting these approaches both spatially and temporally. Beyond this, surveys dependent on such methods have a limited lifespan, the deregulated nature of local level water and sanitation infrastructure and frequency of pit-latrine replacement (Hinton et al., 2023) means that new latrines can be built and used latrines filled before a national survey is even complete. Novel methods are needed to enable *national and dynamic* monitoring of pit-latrines and their associated risks to water-points to enable targeted interventions.

In addition to the contaminants of concern discussed within this thesis (*E.coli* and nitrate in particular), there is need for investigation of other novel contaminants stemming from faecal waste with potential to result in groundwater contamination. Novel contaminants of concern include as contamination from pharmaceuticals within faecal waste as well as and microplastics

(Panno et al., 2019), the implications of these sources are largely understudied (Gwenzi et al., 2023).

9.5.3 Sanitation

Further research is needed to consider the long-term sustainability of improvements in sanitation and steps to ending open defecation, considering measures that can be taken to minimise the risk of slippage of progress to sanitary provision. Future research should particularly emphasise aspects of sanitation provision that consider the needs of vulnerable people.

Locally managed improvements in sanitation such as pit-latrine emptying should be further explored, including community involvement in the development of these solutions, their successful promotion and barriers to adoption.

Barrier analysis of challenges to good-practice in hygiene (such as handwashing and MHM) should also be conducted to identify how policy-makers and stakeholders can better promote improvement in hygiene behaviour.

9.6 Conclusion

In conclusion, the growing needs in water, sanitation, and hygiene present significant challenges for Malawi in achieving SDG6. Throughout this thesis, multiple challenges and potential solutions have been discussed, shedding light on the complex interplay between water resources, sanitation infrastructure, and hygiene practices while emphasising the importance of developing a holistic perspective in both understanding these challenges and finding solutions.

The thesis has proposed several policy recommendations and future research directions to address these challenges and better promote solutions. These include enhancing modelling efforts to better understand water resources, promoting high-quality sanitation systems, and fostering community engagement in water and sanitation management. In doing so, this thesis serves as a step towards addressing the pressing water, sanitation, and hygiene needs in Malawi. By adopting a comprehensive approach and considering the interconnectedness of multiple facets of SDG6, it informs progress and enhances understanding in order to move closer to achieving SDG6 and ensure access to clean water and sanitation for all in Malawi.

Chapters 10 & 11: Appendices

Communicating findings

"Science isn't finished until it's communicated. The communication to wider audiences is part of the job of being a scientist, and so how you communicate is vital" Mark Walport.

Chapter 10: Appendix A: WellPlaced

The conflicts in land and water management and challenges to SDG6 explored within the thesis served as a catalyst for the design of the game "WellPlaced." "WellPlaced" is designed to simulate some of the spatial considerations involved in balancing land and water management decisions, particularly in the context of meeting the requirements of growing population centres while facing environmental hazards and resource limitations. Played on a hexagonal board, the game tasks players with cooperatively managing finances, agricultural activities, and infrastructure placement to ensure the health and well-being of villages, all while navigating floods, droughts, and contamination risks. Following conceptualisation, a grant was sought from the Scottish Environment, Farming, and Agriculture Research Institutions (SEFARI) through their Innovative Knowledge Exchange Fund to enable further development. The subsequent game development resulted in both a physical board game prototype and a digital game, providing flexible platforms for education and stakeholder engagement. The game has been discussed within a blog post, presented here, as well as a poster presented at an international conference, EGU24.

The references are supplied below:

Hinton, R. & Loades, K. "Using serious gaming to communicate challenging concepts in water and land management". SEFARI. 12 June 2013. https://sefari.scot/blog/2023/07/12/using-serious-gaming-to-communicate-challenging-concepts-in-water-management

Hinton, R. and Loades, K.: WellPlaced: Cooperatively navigating challenges to land and water management to reach SDG6, EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-17108, https://doi.org/10.5194/egusphere-egu24-17108, 2024.

10.1 Blog post for SEFARI gateway

Using serious gaming to communicate challenging concepts in water and land management

12 Jul 2023

Serious gaming is a growing field in which games are used to provide a fun and educational method of science communication. Gaming offers opportunities in communicating challenging and complex issues to stakeholders and communities to improve land management practices.

Through a SEFARI Gateway funded Innovative Knowledge Exchange project, we are developing a game highlighting the challenges in land and water-management in Malawi. In addition, we are also investigating the opportunities on how we might use what we've learnt to develop a similar game relevant to the challenges more applicable to the Scottish context.

The highly interconnected nature of the many factors influencing land and water management can make communicating management options a challenge. Balance is key, managing economic, health, social, and environmental requirements within the limitations of land and water availability. Furthermore, the "out of sight, out of mind" nature of groundwater can exacerbate challenges in exploring and communicating management options. This challenge was highlighted whilst researching how Malawi can provide its growing population with the sanitary provisions it requires whilst also protecting its groundwater resources and preventing contamination. Such research builds on strong relationships between Malawi and Scotland as part of the Hydro Nations programme funded by the Scottish Government.

To communicate how these boundaries must be juggled we devised an interactive representation of some of the challenges facing land and water management in Malawi; and create a game called 'WellPlaced'. The game enables players to test multiple management strategies in a fun and engaging manner and it is key to ensure that the growing population remains healthy.

Played out on a hexagonal board, the game centres around meeting the requirements of the population centres represented as "villages". Each village requires access to sanitation and water to maintain their health, however, players must have enough finances to pay for such infrastructure. Money is generated through the growing and selling of produce grown on "farm tiles". Throughout the game, players convert tiles to meet requirements and must face environmental hazards such as floods, drought, and contamination. The likelihood of such natural hazards can be exacerbated by the decisions players make, for example, removing "tree tiles" increases the risk of drawing a flooding hazard card.

As well as developing a physical prototype of the game we have been working with partners at the University of Abertay, to also created a digital prototype. Both games can be played collaboratively, with multiple players, prompting discussion of how to balance priorities in land and water management and simulating many of the conversation's, and decisions, that communities will have to make. The game provides a valuable tool for both education and stakeholder engagement. We are working on devising some tests of the game to explore how it communicates the key concepts.

"Water borne disease" hazard was drawn!

Image: Digital Game Prototype developed alongside students at the University of Abertay.

Developing a game to communicate the challenges within a Malawian context has helped with exploring the concept of also designing a serious game to discuss land and water management in Scotland. The Scottish context will have a much stronger urban focus with challenges in water management such as urban flood management being a core consideration. Factors such as peatland management are also a particularly significant consideration within a Scottish context. As in the case of the Malawi game, it has been an important learning-curve in communicating complex systems in a streamlined format. Funds have enabled us to hold several meetings between interested partners from several SEFARI organisations so we can build on the idea of how a serious educational game might be a useful resource regarding Scottish land and water management. Developing a network of stakeholders involved in land and water management who are keen to communicate these concepts within an interactive format has been particularly enlightening in identifying key areas of land and water interacts that would be most beneficial to communicate. In the future, we are aiming to drive these ideas further forward, so watch this space as we aim to make science communication informative as well as seriously fun!

Rebekah Hinton and Kenneth Loades (James Hutton Institute)

10.2 EGU24 Poster Presentation

Abstract:

WellPlaced: Cooperatively navigating challenges to land and water management to reach SDG6

Rebekah Hinton and Kenneth Loades

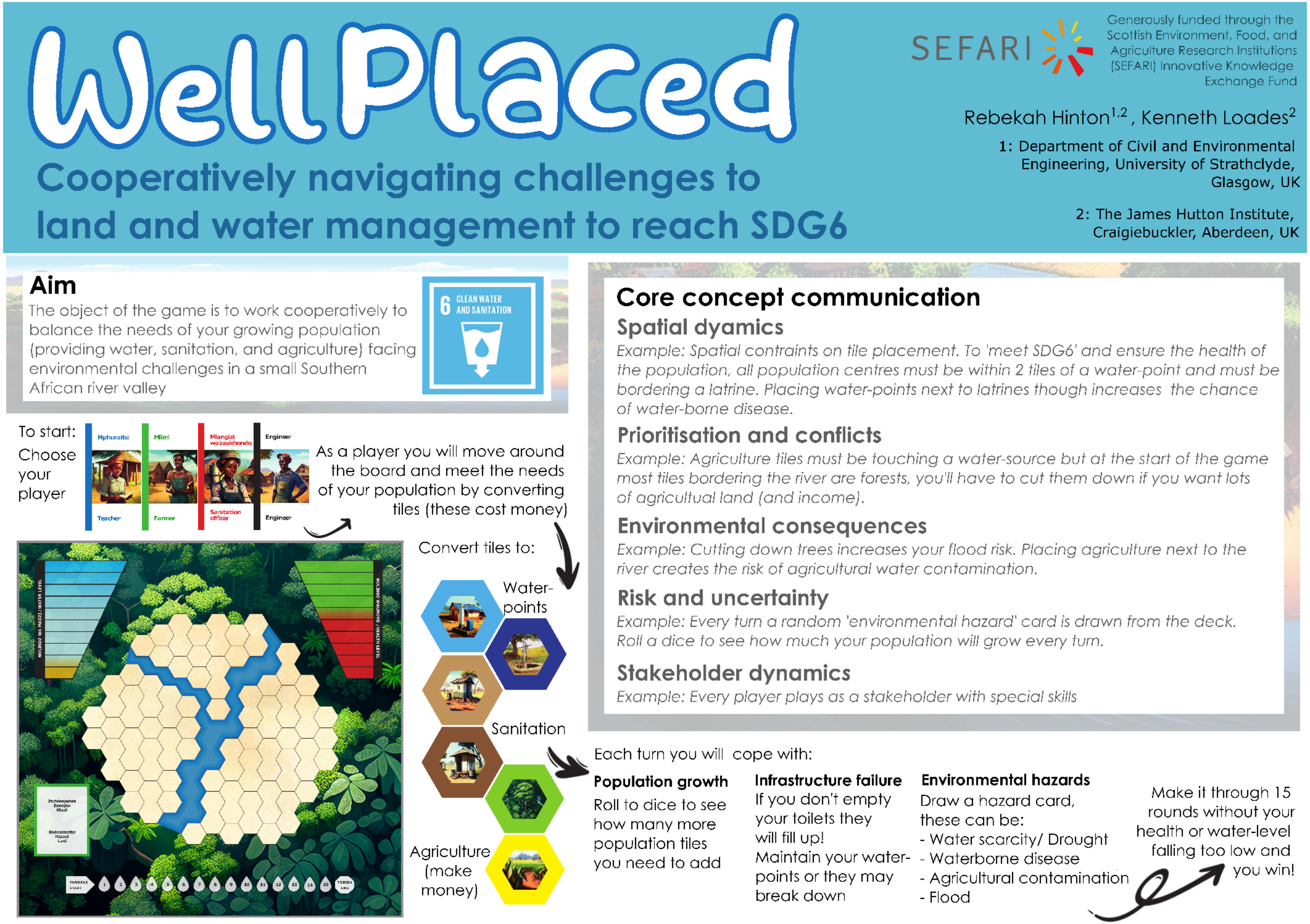
Introducing 'WellPlaced,' an interactive and collaborative game designed as a unique tool for illustrating the intricate dynaMICS of land and water management, with a specific focus on the context of Malawi. Played on a hexagonal board, 'WellPlaced' revolves around the vital task of meeting the requirements of population centres, depicted as ‘villages’. Each village demands access to sanitation and water for health maintenance, requiring players to manage their finances, generated through agricultural activities on ’farm tiles’. The spatial component of the game reflects the spatial dynaMICS of land and water management, particularly regarding availability of water resources and risk of contamination. For example, all villages must be within an appropriate distance of water and sanitation facilities, but latrines cannot be placed adjacent to water-points. As the game progresses and the population grows, increasingly quicker, navigating the growing pressures on land and water use becomes even more challenging.

As players convert tiles to meet these requirements, they confront random environmental hazards including floods, droughts, waterborne disease, and contamination, with player decision making influencing the likelihood of encountering such challenges. For example, removing forest tiles, freeing up their valuable, riverside hexes as well as returning a small amount of money for ‘selling the lumber’, adds more flood risk cards to the pack, increasing the chance of players encountering more flooding. The probabilistic nature of such events helps to communicate risk in an engaging format. The ‘out of sight, out of mind’ nature of groundwater necessitates innovative and creative methods to explore and communicate groundwater challenges and management options effectively. Alongside random environmental hazards,

overuse of groundwater can deplete the aquifer represented in the game, drawing attention to considerations of sustainable groundwater use.

Players must work together to navigate the needs of the growing population, keeping their population healthy throughout multiple rounds. Each player adopts a role, representing a stakeholder within the nexus and prompting conversations about different agendas and skillsets within land and water management decision making. Each game involves an engineer, sanitation officer, teacher, and farmer, each having specific capacities and skills. For example, water and sanitation management education programmes can be facilitated by the teacher, providing innovative solutions to problems experienced in the game.

'WellPlaced' not only provides an engaging platform for understanding the complexities of land and water management in Malawi but also fosters collaborative conversations among players, representing various stakeholders, and serves as an innovative tool for exploring sustainable solutions and challenging decision-making scenarios.



WellPlaced

Cooperatively navigating challenges to land and water management to reach SDG6

SEFARI
Generously funded through the Scottish Environment, Food, and Agriculture Research Institutions (SEFARI) Innovative Knowledge Exchange Fund

Rebekah Hinton[1,2], Kenneth Loades[2]

1: Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, UK

2: The James Hutton Institute, Craigiebuckler, Aberdeen, UK

Aim

The object of the game is to work cooperatively to balance the needs of your growing population (providing water, sanitation, and agriculture) facing environmental challenges in a small Southern African river valley

To start: Choose your player

As a player you will move around the board and meet the needs of your population by converting tiles (these cost money)

Convert tiles to:

Water-points

Sanitation

Agriculture (make money)

Core concept communication

Spatial dyamics

Example: Spatial contraints on tile placement. To 'meet SDG6' and ensure the health of the population, all population centres must be within 2 tiles of a water-point and must be bordering a latrine. Placing water-points next to latrines though increases the chance of water-borne disease.

Prioritisation and conflicts

Example: Agriculture tiles must be touching a water-source but at the start of the game most tiles bordering the river are forests, you'll have to cut them down if you want lots of agricultural land (and income).

Environmental consequences

Example: Cutting down trees increases your flood risk. Placing agriculture next to the river creates the risk of agricultural water contamination.

Risk and uncertainty

Example: Every turn a random 'environmental hazard' card is drawn from the deck. Roll a dice to see how much your population will grow every turn.

Stakeholder dynamics

Example: Every player plays as a stakeholder with special skills

Each turn you will cope with:

Population growth
Roll to dice to see how many more population tiles you need to add

Infrastructure failure
If you don't empty your toilets they will fill up!
Maintain your water-points or they may break down

Environmental hazards
Draw a hazard card, these can be:
- Water scarcity/ Drought
- Waterborne disease
- Agricultural contamination
- Flood

Make it through 15 rounds without your health or water-level falling too low and you win!

Chapter 11: Appendix B: Navigating the pitfalls

A significant contribution of this thesis was the exploration of the interconnection between sanitation and groundwater, particularly the implications of pit-latrines on water-borne disease, in Malawi. To communicate some of these challenges in an accessible format, an explanatory piece was produced for the magazine Appropriate Technology, March 2024, and is provided here.

The references is given below:

Hinton, R.. 2024. Navigating the pitfalls: how to manage pit-latrines and water borne disease. Appropriate Technology, Vol 51, No.1. March 2024. ISSN 1751-6900.

Navigating the pitfalls: how to manage pit-latrines and water borne disease

By Rebekah Hinton

The eradication of waterborne diseases and meeting sustainable sanitation goals is critically important for human health, well-being and sustainable development.

One of the measures taken to address these goals has been a large focus on the use of pit latrines.

Their use in helping to reduce open defecation is crucial. However, it is also complex and introduces a paradox in that, not properly managed, pit latrines can cause groundwater contamination.

These challenges are particularly acute in Malawi, where water, sanitation and hygiene infrastructure are challenged. Some 82% of the population lack access to safely managed drinking water, while more than 90% rely on pit latrines, that – not properly managed – contribute to groundwater contamination.

Targeted interventions are needed to break the cycles that affect those most impacted – who are also most vulnerable members of our global community.

This article explores the challenges, looks at the risks posed by poor pit latrine construction, contamination and inadequate decommissioning and suggests innovative interventions.

11.1 The burden of waterborne diseases


Waterborne disease represents a significant burden, particularly for many of the most vulnerable communities globally. Ensuring that water-points like these remain free of waterborne disease is a critical health and development priority.

The burden of waterborne diseases is an alarming global challenge, significantly impacting public health and particularly affecting the most vulnerable segments of society.

According to UNICEF (2023), insufficient water, sanitation, and hygiene (WASH) conditions are responsible for the deaths of more than 1,000 children under the age of five, every day, globally.

The World Health Organisation (WHO) estimates that waterborne disease is responsible for 10% of the global disease burden (WHO, 2012).

Of the global deaths resulting from unsafe WASH conditions, a substantial 40% occur in just 10 countries, all concentrated within Sub-Saharan Africa (UNICEF, 2023).

In the case of Malawi, inadequate WASH has been identified as contributing to more than half (52%) of the disease burden (UNICEF, 2021). Diarrheal disease alone, often stemming from contaminated water sources, accounts for 7% of deaths in children under five in Malawi (Moon et al., 2019).

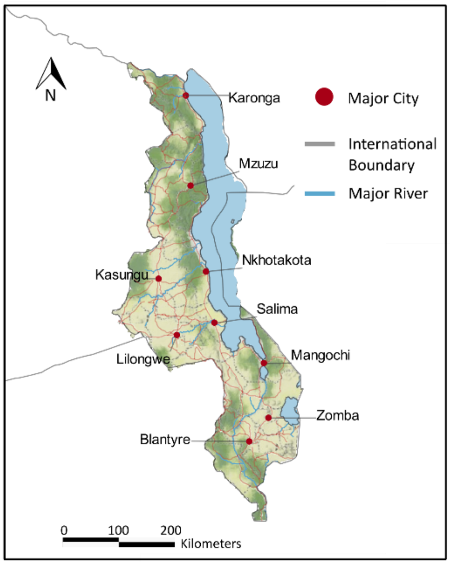
Case study: cholera and climatic events
Cholera highlights the impact of climatic events on waterborne diseases and the consequences. It is caused by the consumption of water or food contaminated with *Vibrio cholerae* bacteria and is experienced as an acute diarrheal infection, often leading to death within hours if left untreated (WHO, 2023). There are around 3 million cholera cases annually, resulting in 95,000 deaths within endemic countries (Ali et al., 2015). Despite hard-won progress in combating this preventable disease through extensive vaccination campaigns (UNICEF Supply Division, 2022), control efforts face a formidable challenge from extreme weather events that cause water contamination. Malawi's worst cholera outbreak in 2023 was caused by heavy flooding, due to tropical cyclones, and led to 8,982 cholera cases and 1,768 deaths (WHO Malawi, 2023). Minimizing the ability for extreme weather to cause cholera surges plays a pivotal role in building climate resilience (Asadgol et al., 2020; Christaki et al., 2020; Gina et al., 2022). Beyond the need for climate resilience in managing waterborne diseases, the social inequality of the cholera burdon, which disproportionately affects the world's poorest nations and communities, elevates cholera control to a critical climate justice issue (ActionAid, 2022).

But there are also concerns beyond health in the immediate term. Climate change, as a driver of extreme weather events, has been identified as a catalyst for waterborne disease outbreaks (Rivett et al., 2022). The anticipated increase in the frequency and intensity of such events underscores an urgent need for comprehensive strategies to mitigate the impacts on vulnerable communities.

Sub-Saharan Africa, in particular, has experienced a tenfold increase in the number of floods since 1970–79 (World Bank, 2021). Together, UNICEF has named disease, climate change and unsafe WASH have a “deadly combination” for children, highlighting the urgent need for a holistic approach that addresses all three interconnected challenges (UNICEF, 2023).

11.2 Malawi as a key focus area

Malawi faces particular challenges in this area. The south-east African country has a population of more than 20 million, a number expected to grow five-fold this century (Worldbank, 2023, with 70.1% living below the international poverty line of $2.15 per day (Worldbank, 2019). It also has a high rural population (84%) (Malawi 2063- NSO, 2020), with more than 80% of the population engaged in agriculture, making the nation susceptible to climate shocks.



Our studies focus on Malawi, a country in southeastern Africa which has a particularly high burden of waterborne disease and a large proportion of the population with inadequate access to WASH infrastructure.

The increasing severity and frequency of tropical cyclones and droughts have inflicted considerable harm, affecting not only lives but also the economy and environmental resources, including groundwater supplies.

Evolving urbanization, with a planned 60% urban population by 2063, presents additional challenges, particularly in addressing informal settlements and inadequate housing, where 60% of the urban population currently resides in slum areas (Malawi 2063).

These challenges, alongside government endeavours to achieve 100% access to safely managed sanitation (Hinton et al., 2023), make the expansion of sanitation infrastructure a critical issue for Malawi.

They also make Malawi stand out as an essential focal point for the examination of innovations in WASH solutions and how to combat against waterborne diseases against a confluence of factors.

11.3 Malawi’s WASH infrastructure

Currently, 82% of Malawi’s population lacks access to safely managed drinking water (UN, 2023), a level significantly below the Sub-Saharan African average of 31%.

The majority of Malawi’s drinking water sources are rooted in groundwater, a vital resource sustaining 85% of the population (Graham & Polizzotto, 2013). Boreholes and tube wells contribute significantly, comprising 64% of the improved sources of drinking water (MICS, 2021). However, 60% of the population relies on drinking water sources containing measurable E. coli, while 16.5% face exposure to over 100 faecal coliforms per 100ml (MICS, 2021).

Example functional borehole in Malawi. Groundwater provides the main source of drinking water for over 85% of the population of Malawi, with 64% of improved sources of drinking water being boreholes and tubewells like this. Microbial contamination is a major concern

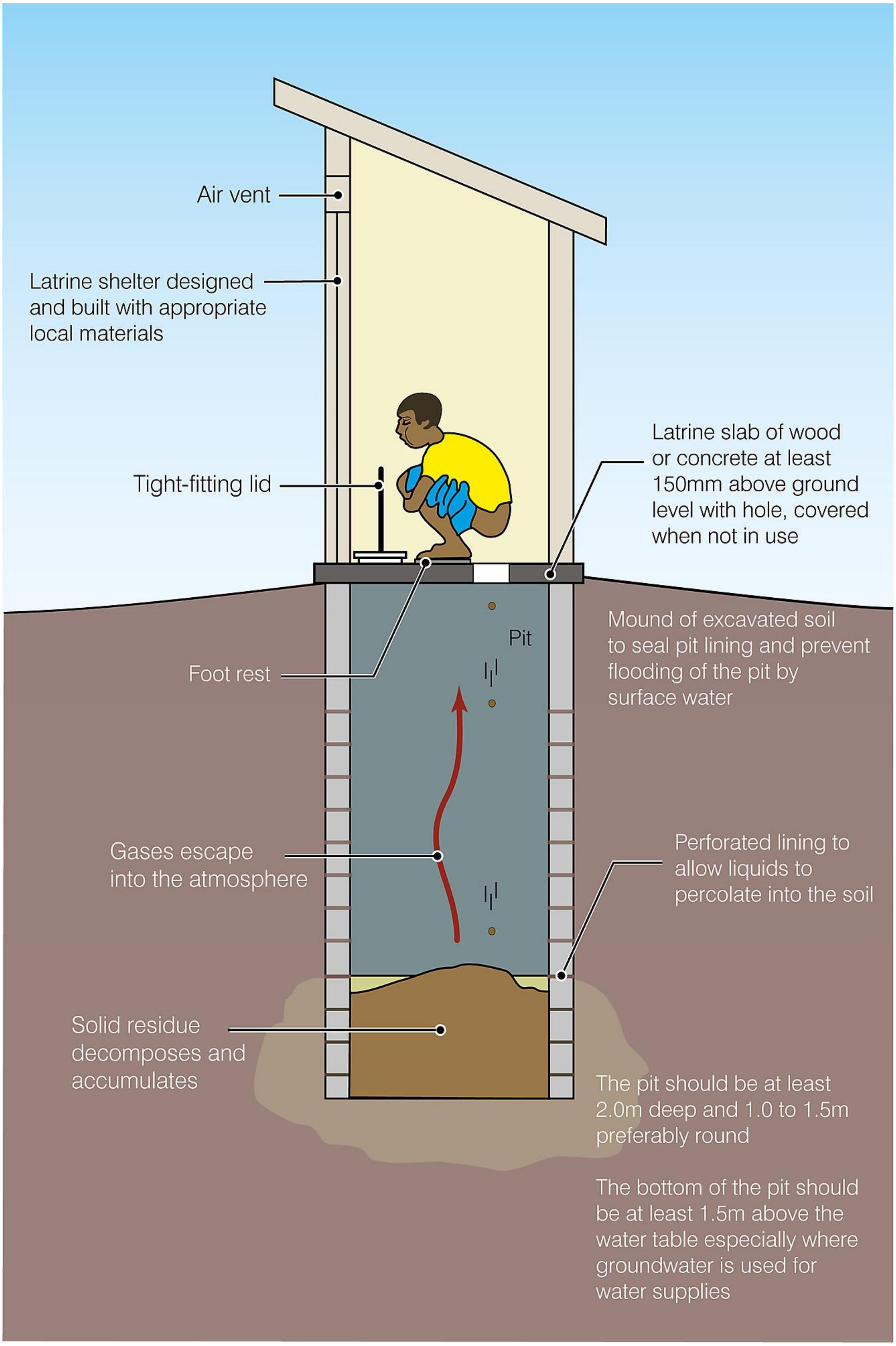
for such waterpoints with over 60% of the population having measurable E.coli contamination at their drinking water source.

There have been improvements in some areas. Malawi witnessed a significant decline from 27.7% of the population practicing open defecation in 1992 to current estimates indicating just 5.4% use this practice (Hinton et al., 2023). Our research, covering over 200,000 sanitary facilities across Malawi, estimated that 23% of the population accessed improved sanitary facilities, with 24.4% of the total sanitary facilities falling under the improved category (Hinton et al., 2023).

Multiple national surveys indicate that more than 90% of the population primarily relies on pit latrines as their main source of sanitation (Hinton et al., 2023).

11.4 Pit latrine construction

Pit latrines typically consist of a pit dug into earth into which faecal waste is deposited. Latrine facilities are typically constructed around 10m from the home to manage nuisance from odours and flies (although this varies) (Reed, 2014).


Air vent
Latrine shelter designed and built with appropriate local materials
Tight-fitting lid
Latrine slab of wood or concrete at least 150mm above ground level with hole, covered when not in use
Mound of excavated soil to seal pit lining and prevent flooding of the pit by surface water
Pit
Foot rest
Gases escape into the atmosphere
Perforated lining to allow liquids to percolate into the soil
Solid residue decomposes and accumulates
The pit should be at least 2.0m deep and 1.0 to 1.5m preferably round
The bottom of the pit should be at least 1.5m above the water table especially where groundwater is used for water supplies

Pit latrine construction specifications. McMahon, Glenda; Shaw, Rod (2019). Simple pit latrine 6. Loughborough University. Figure. https://doi.org/10.17028/rd.lboro.7945937.v1

Pits are typically dug by hand and have varying dimensions, according to personal preference (Reed 2014). In Uganda, pits are often over 8m deep whilst other pits are typically around 1.5m deep (Reed 2014). The pit is advised to be a circular construction to increase stability and is recommended to be lined with a semi-permeable material.

The top 0.5-1m of the pit-latrine is always recommended to be lined, commonly with bricks, stone, concrete or with timber. This lining is to provide structural stability and support, minimising latrine collapse. The lining also minimises surface water from entering the pit. In emergencies, sandbags can also be used to provide a lining material. In loose soil, likely to collapse, pit-latrines are recommended to be lined fully. This is also recommended in cases where the latrine is likely to be emptied (Reed, 2014). However, despite lining being recommended, pit-latrines frequently fail to meet this construction quality. In Malawi, where 86% of pit-latrines are unlined (Hinton et al., 2023b), this presents a serious concern for latrine collapse.

Following pit construction, a superstructure is built to cover the facility, provide privacy and prevent the pit filling with rainwater. Construction varies considerably, but it typically from brick or timber, although some can be cloth fastened to pieces of wood. Construction quality is poor in Malawi with over 35% of pit-latrines having no roof, inadequate privacy and over 75% not offering security (Hinton et al., *under review*).

It is recommended that the floor of the latrine is fitted with a concrete slab (figure), to increase hygiene and structural integrity, however, over 75% of the 200,000 latrines surveyed in Malawi did not have a concrete slab (Hinton et al., 2023). Further improvements can be made to latrine structures by fitting odour controlling devices or flush pouring systems (Gwenzi et al., 2023).

https://www.bbc.co.uk/news/world-africa-45183593. Pit-latrines, like these, form the backbone of sanitation systems for much of sub-Saharan Africa. In Malawi, pit-latrines provide sanitation for over 90% of the population. However, limited regulations, poor construction quality and high densities of pit-latrines may mean that this essential resource in sanitary provision can cause dire consequences for groundwater contamination.

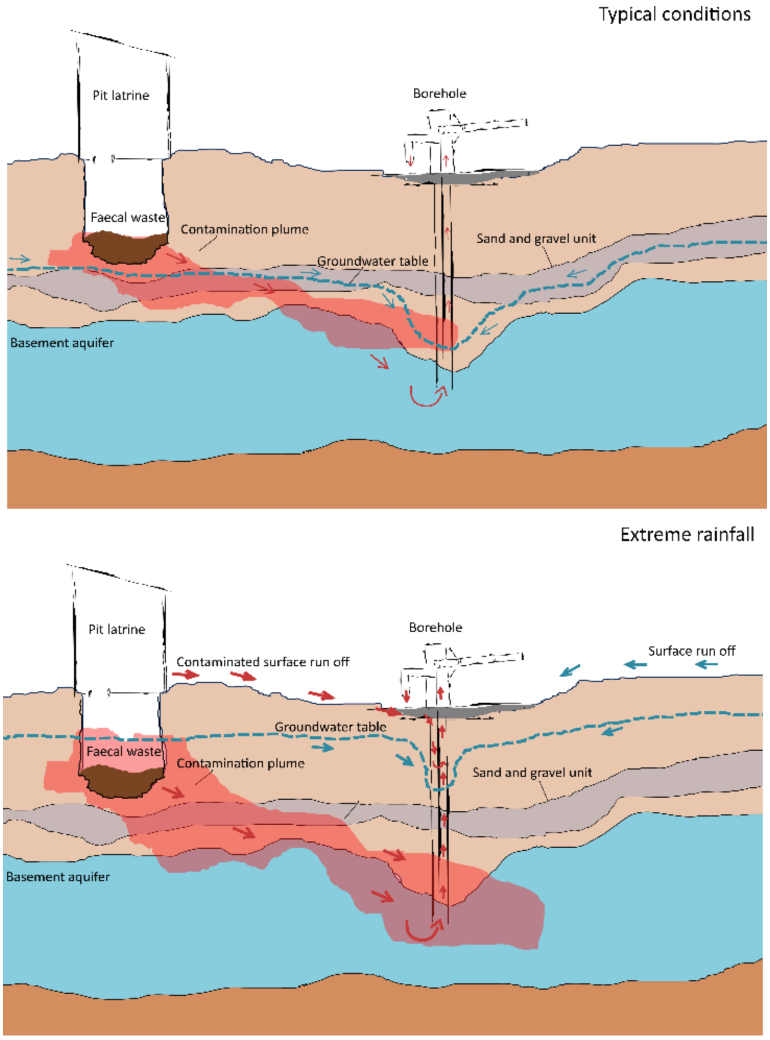
https://washresources.cawst.org/en/resources/e375ee5c/how-to-make-a-reinforced-concrete-slab. A pit-latrine constructed with a concrete slab. Best practice recommends that pit-latrines are constructed with a concrete slab to enable easy cleaning as well as to minimise light and insects entering the pit.

11.5 The pit-latrine dichotomy for SDG6

Pit-latrines involve digging a pit in the earth for excreta disposal. In Malawi, they have been instrumental in significantly reducing open defecation, making crucial contributions to advancing Sustainable Development Goal 6 (SDG6) and improving WASH infrastructure.

However, in Malawi, only 14% of pit-latrines have any lining and merely 24% feature a concrete slab, deviating from best practices explained above (Hinton et al., 2023). This turns pit-latrines into potential pollution hotspots and reservoirs of contaminants, putting groundwater and surface water at risk (Gwenzi et al., 2023; Graham & Polizzotto, 2013).

So while pit-latrines contribute significantly to the reduction of open defecation and align with SDG6 objectives, not adhering to construction best practices risks groundwater contamination, undermining SDG6 goals related to safe water and sanitation.



Pit-latrine contamination of groundwater supplies under standard weather conditions and under flooding/ extreme rainfall. Extreme rainfall increases groundwater contamination risk from pit-latrines through the dual risk of raised water-table and contamination from surface run-off.

11.6 Managing planning and decommissioning

A key aspect of effectively managing the risk of drinking water pollution from pit-latrines involves maintaining a suitable distance between these facilities and water-points. However, establishing a universally accepted ‘safe’ distance is challenging, with guidelines varying from 100m to under 10m (Banerjee, 2011; Chidavaenzi, et al., 2000; Franceys et al., 1992; Reed, 2014; Sphere Association, 2018; Water Aid, 2013). Compounding this challenge is the unregulated nature of pit-latrine construction (Nya et al., 2022), which makes the enforcement of construction standards and adherence to safe distances impossible.

We also found that many pit-latrines are replaced every 2-3 years, complicating the management and monitoring of distances to water-points (Hinton et al., 2023). A common (bad) practice of abandoning filled latrines without proper treatment also poses ongoing environmental and public health risks.

Inappropriate management of disused pit-latrine facilities following abandonment further exacerbates the public health hazards they pose. Decommissioning guidelines recommend dismantling the latrine superstructure, filling the latrine with lime to eliminate pathogens and covering it with debris or planting a tree on it, to identify it as previously been a pit-latrine location (WASH Cluster Mozambique, Still et al., 2002). Despite these recommendations, we found that 58.4% of decommissioned latrines underwent no decommissioning process at all, posing a public health risk due to exposed human waste (Hinton et al., 2023).

The risk of drinking water contamination from pit-latrines is heightened during extreme rainfall and flooding, leading to contaminated surface runoff and a rise in the groundwater table, as shown in Figure 1. The aftermath of Cyclone Idai in Malawi, in March 2019, illustrated the consequences of extreme rainfall on groundwater contamination (Rivett et al., 2022); the link between extreme weather events and pit-latrine contamination risk is closely linked to the proximity and density of pit-latrines to water-points.

This is therefore a critical consideration in maintaining drinking water safety. Ensuring appropriate pit-latrine construction and management can also minimise water contamination as a result of flooding events.

11.7 What can we do?

Pit latrines will remain pivotal in the sanitation strategies of many low and middle-income countries. It is crucial to continue investing in and promoting their proper usage, recognizing their significance in reducing open defecation.

In areas with high pit-latrine density, especially where groundwater is heavily used for drinking water, as in Malawi, exploring alternatives becomes important. Piped sanitation is an option, although it is expensive, disruptive to implement, requires sewage works construction, takes time and may not be feasible in informal residential areas. Decentralized sewage treatment systems can be more feasible but are still not always a viable option.

Septic tanks offer another option but come with high costs and the potential for groundwater contamination. The management of pit-latrine usage, ensuring appropriate use and effective management, will continue to be critical in navigating these challenges.

11.8 Areas of intervention

We propose focusing on three key aspects of pit-latrine construction and use to lower their impact on water supplies.

11.8.1 Appropriate construction

A focus on appropriate pit-latrine construction practices is paramount. Initiatives should include promoting proper pit-latrine lining with the use of low-cost and readily available materials, through educational programs. Construction should adhere to guidelines, ensuring an appropriate distance from water points, and efforts should be made to enhance community understanding of risks to groundwater contamination.

Clear delineation of responsibilities in borehole management can serve as a preventive measure, ensuring that water point committees have appropriate capacity to safeguard water-points from pit-latrine contamination and have the knowledge to minimise pit-latrine contamination. Pit-latrine lining should also be promoted, including use of lining materials that minimise contamination, as well for structural purposes, and promoting full lining of the pit.

Construction of pit-latrines should also consider the risk of extreme weather events, particularly flood risk, considering alternative sanitation facilities and giving an even greater focus on construction quality in high-risk areas. Considerations of hydrogeology within an area can further inform where pit-latrine use is appropriate; for example, local preferential groundwater flow patterns and groundwater table depth can minimise groundwater contamination (Hinton et al., 2023 – in review).

Case-study: Biochar production from faecal waste

In an unassuming corner of Blantyre, Malawi, just beyond where the rows of residential houses begin to fade away, lies a transformative centre. A group of entrepreneurs is using faecal waste, emptied from pit-latrines, to produce biochar – an ecological charcoal substitute.

The occasional beep of a delivery truck signals the arrival of a fresh batch of waste, emptied from pit-latrines in the nearby city. The emptied latrines can continue to provide sanitation services and the high rate of pit-latrine filling and abandonment is minimised.

The faecal waste is first dried in drying beds, killing pathogens within the waste and producing a powered, carbon-rich material. To effectively dry the waste, the material is first 'dewatered' by filtration through gravel before being dried in the sun, for weeks or months until free of moisture.

The waste is then heated to high temperatures to thermally decompose the carbon-rich waste, in an oxygen-free environment, producing 'biochar', a form of charcoal.

The biochar is sold as a charcoal alternative, offering a cheaper source of fuel and providing an alternative to the ecologically devastating charcoal industry.

Biochar production process: Nicholas et al., 2023

11.8.2 Management and monitoring of use

The management and monitoring of pit-latrine use is also critical and, given their largely informal construction, innovative monitoring techniques are imperative.

Advocating for frequent pit-latrine emptying is essential to limit chemical and microbial contaminant leakage into groundwater. Exploring emerging techniques, such as treating sanitation as a business or using waste for fertilizer and biogas production, could introduce economic incentives. These approaches could also involve alternative uses, such as making briquettes from biochar (Gwenzi et al., 2023).

An example of biochar produced from faecal waste emptied from pit-latrines. The biochar also has the benefit of providing a sustainable charcoal source, providing an alternative to traditional charcoal production that is heavily driven by deforestation.

11.8.3 Pit-latrine decommissioning.

Finally, appropriate decommissioning practices are crucial. Implementing effective strategies for managing decommissioned pit-latrines is vital to address environmental and public health concerns associated with abandoned facilities. Steps in decommissioning should manage contamination risks (such as adding lime or another disinfectant to the latrine), covering the disused structure and demarcating the area to make it clear that it is a decommissioned latrine (WASH Cluster Mozambique, Still et al., 2002.).

Overall, a comprehensive approach to pit-latrine construction and use, spanning appropriate construction, management, monitoring, and decommissioning is essential for sustainable sanitation practices.

As pit-latrines remain integral to sanitation strategies in many low and middle-income countries, a holistic approach that recognises their pitfalls and risks of groundwater contamination, as well as their value, is critical. Immediate and concerted global efforts

are required address and manage the paradoxical nature of pit-latrines and to work more effectively towards improving health, sustainable development, and climate justice.

Rebekah Hinton is a researcher into land and water use in Malawi, with a focus on groundwater contamination. She is a PhD student with the University of Strathclyde and the James Hutton Institute.

Chapter 12: Appendix C: Ethical approval

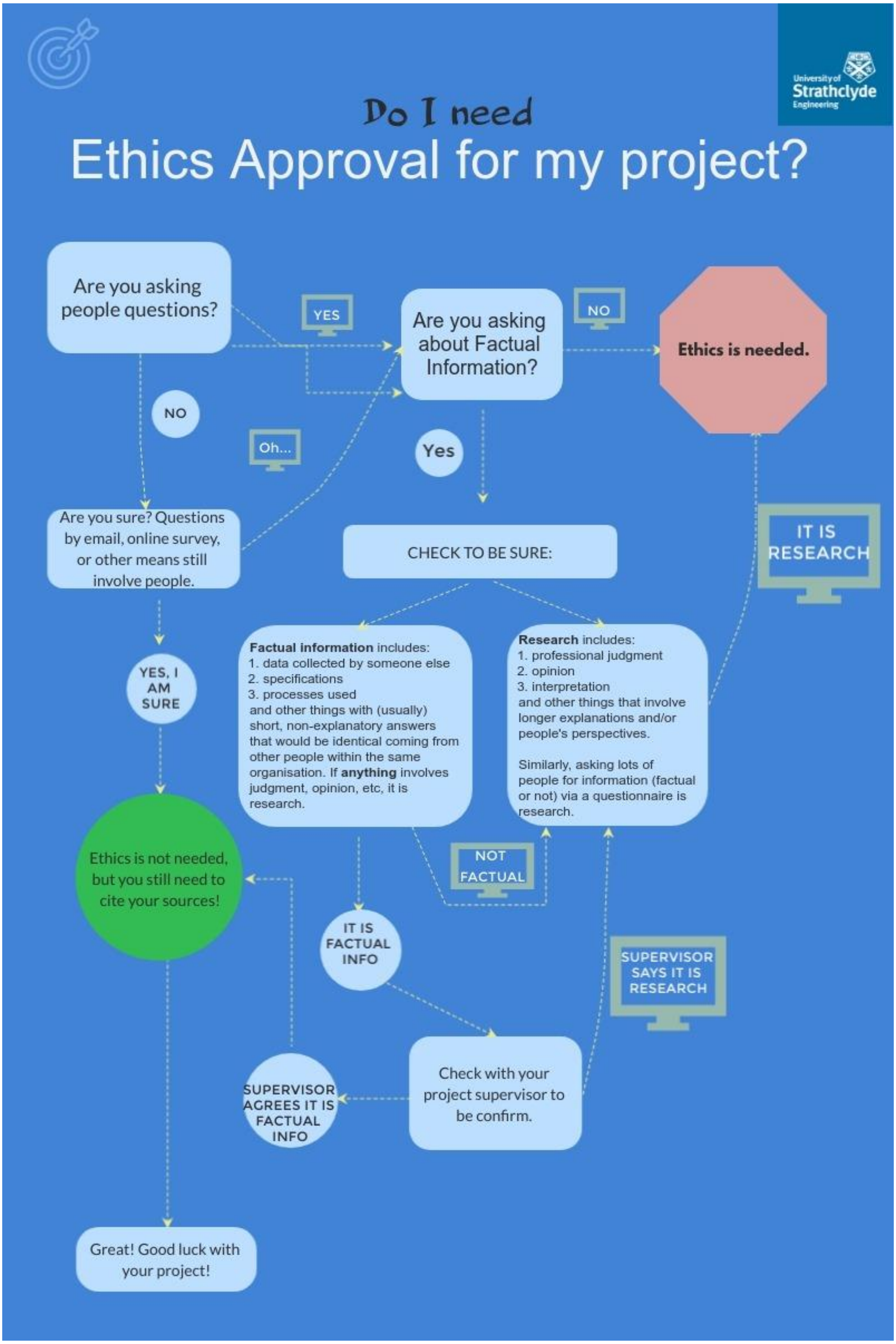
Ethical approval was sought at multiple stages of this thesis following guidance from the University of Strathclyde Ethical Approval guidelines, shown in Figure 12.1

Ethical approval was required where research was conducted that included a participants' opinion, professional judgement, or interpretation. Within this thesis, ethical approval was sought for a series of stakeholder interviews taking place in October 2022 gaining perspective on areas of concern and priority within water and sanitation issues of stakeholders from Government, NGOs, and businesses. Ethical approval was granted by the James Hutton Institute and is evidenced here.

In addition, ethical approval was granted from IIASA to specifically inform understanding of the construction of a water model for Malawi's water supplies, paper 2. Further information is detailed in chapter 4.

Guidance was sought and guidelines were followed for ethical approval for all other pieces of work. In some cases, ethical approval was not required (the CJF surveys) as the data collected was factual information, Figure 12.1. Data from CARE surveys was also classed as factual information as it was gathered by a third party, here clarification was sought from the Government of Malawi ethics board to ensure compliance with all ethical processes.

In addition, all work was conducted, and co-authored, alongside partners from the Government of Malawi with close adherence to Government of Malawi ethics protocols.



Do I need Ethics Approval for my project?

Are you asking people questions?

YES

NO

Are you asking about Factual Information?

NO

Ethics is needed.

Yes

Oh...

Are you sure? Questions by email, online survey, or other means still involve people.

CHECK TO BE SURE:

Factual information includes:
1. data collected by someone else
2. specifications
3. processes used

and other things with (usually) short, non-explanatory answers that would be identical coming from other people within the same organisation. If **anything** involves judgment, opinion, etc, it is research.

Research includes:
1. professional judgment
2. opinion
3. interpretation

and other things that involve longer explanations and/or people's perspectives.

Similarly, asking lots of people for information (factual or not) via a questionnaire is research.

IT IS RESEARCH

YES, I AM SURE

Ethics is not needed, but you still need to cite your sources!

NOT FACTUAL

IT IS FACTUAL INFO

SUPERVISOR SAYS IT IS RESEARCH

SUPERVISOR AGREES IT IS FACTUAL INFO

Check with your project supervisor to be confirm.

Great! Good luck with your project!

The James Hutton Institute

Response Letter

This is to certify that the procedures, personnel and locations included in the application below have been reviewed favourably by The James Hutton Institute on behalf of the Research Ethics Committee.

Project ID: 0113

Project Title: Ethics Application R Hinton Malawi Groundwater management 2022

Chief Investigator: Ms Rebekah Hinton

Approval Date: #### TOKEN ERROR (CustomData.3171) UNKNOWN ####

Other Listed Investigators: #### TOKEN ERROR (Contact.Type.fullname.109) UNKNOWN ####

Responsibilities:

Investigators have personal responsibility for all matters that relate to this project, and must comply with the actions outlined in the application and all relevant laws, policies and procedures.

Reminders:

- Any variation proposed to the project, and the reasons for that change, must be submitted to the Committee for further review and must not be implemented until agreement is granted in writing;
- The REC must be notified of any unexpected adverse events or potential non-compliance within 3 business days. Where possible, notification should be in the form of an Incident Report submitted in ERM; and

Investigators are required to provide Annual Progress Reports and a Final Report within 3 months of end of approval or discontinuation of the project.

Kind Regards,

Dr Liz Dinnie
Deputy Chair

On behalf of The James Hutton Institute

List of reviewed documents:

Document Type	File Name	Date	Version
Other	mWater survey questions		
Other	Additional questions		
PI/CF Forms	Status of Borehole-Garden Permaculture Ethics Information Sheet		
PI/CF Forms	Consent Form Ethics Status of Borehole-Garden Permaculture 2		

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