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RESEARCH ARTICLE

Persistent groundwater data scarcity: Challenges and advancements from a co-creation process in Malawi

Donald John Charles Robertson[1*], **Sydney Byrns**[2], **Rowan Ellis**[3], **Christopher J. White**[1], **Muthi Nhlema**[4], **Given Ngwira**[5], **Zione Butao**[6], **Mike Myaba**[7], **Macpherson Nkhata**[6], **Tracy Morse**[1]

1 Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow, United Kingdom, **2** Faculty of Natural Sciences, University of Stirling, Stirling, United Kingdom, **3** Edmund A. Walsh School of Foreign Service, Georgetown University in Qatar, Doha, Qatar, **4** BASEflow, Blantyre, Malawi, **5** IsraAID Malawi, Blantyre, Malawi, **6** Department of Water Resources, Ministry of Water and Sanitation, Government of Malawi, Lilongwe, Malawi, **7** National Water Resources Authority, Lilongwe, Malawi

* donald.j.robertson@strath.ac.uk

Abstract

Groundwater monitoring is essential to sustainable water resource management and climate resilience strategies – a source of key data to support decision-making. However, in many regions of the world including in Malawi, a country that is heavily reliant on groundwater, the scarcity of groundwater monitoring data is a persistent challenge. The scarcity of data is compounded by the in-operation of existing groundwater monitoring networks. While operational challenges have often been framed as a technical or financial issue, this study applies a co-creation methodology to explore the wider institutional, procedural, and social factors contributing to persistent data scarcity. Drawing from sourced grey literature and a series of participatory workshops held in Malawi with stakeholders from across the water sector, including community representatives, several systemic and interconnected challenges were identified. Themes of challenges include institutional and governance fragmentation, procedural ambiguity, limited and uncertain financing, and a lack of formalised community engagement. Participants emphasised that these challenges are not independent and addressing them in isolation is unlikely to lead to long-term improvement in data availability. Instead, data scarcity is a symptom of deeper systemic issues, and any attempt to improve the monitoring network must consider the broader context in which it operates. The findings suggest that future efforts, in Malawi and in other global contexts, should prioritise adaptive and inclusive strategies, including strengthened institutional coordination, updated procedural guidance, and an expanded role for community participation in monitoring activities.

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1. Introduction

1.1. The global significance of groundwater

Groundwater is Earth's largest accessible source of fresh water, constituting 90% of the available fresh water supply [1]. It plays a critical role in sustaining our societies, supplying potable drinking water, supporting the health of surface water systems, enabling agriculture and irrigation and underpinning wider sustainable development under the United Nations Sustainable Development Goals (SDGs) [1,2]. In regions like sub-Saharan Africa (SSA), as much as 80% of the population are reliant on groundwater for drinking water [3,4]. Although precise estimates of groundwater use in Africa are difficult [3], the importance of groundwater to regional water security and supporting human health and wellbeing is widely recognised [5–7].

Like other sources of fresh water, groundwater is vulnerable to changing climatic patterns and the effects of anthropogenic activities [8–11]. It is, however, generally less prone to short-term climate shocks and extremes, making it important for climate- resilience planning [8]. While changing water demands and environmental inputs can pressure groundwater sustainability in some contexts [12,13], groundwater is also recognised as a climate-resilient source of fresh water in others [6,10,12,14,15]. Consequently, understanding and managing long-term trends of groundwater quantity and quality is increasingly important for policymakers.

1.2. Understanding groundwater: Data scarcity and knowledge gaps

To manage groundwater sustainability, detailed groundwater resource assessments should be carried out and considered alongside socio-political conditions [16,17]. These assessments rely on the availability of robust groundwater data, including from routine monitoring [17] and are most valuable when linked to clear management objectives such as monitoring how groundwater systems respond to recharge, abstraction and wider environmental change While earth observation techniques are increasingly valuable for these purposes, they do not offer a substitute for in situ monitoring [15].

The provision of in situ groundwater data (e.g., water level, temperature, piezometric head, water quality) has relied on a network of monitoring stations, typically managed at a national level by government-led authorities. Although research notes the expansion of water monitoring networks in global totality [18] groundwater monitoring is highly variable in terms of data availability and quality across the world [19,20]. SSA, in particular, is characterised by a lack of groundwater monitoring networks and a scarcity of available monitoring data [19,21–23]. This lack of data poses a significant challenge for water managers and hinders progress towards achieving Sustainable Development Goal 6, Clean Water and Sanitation [19,22–25] and the implementation of Integrated Water Resources Management (IWRM), as well as the utilisation of emerging modelling tools and techniques [15,26–30].

While generating and using data is essential to understanding groundwater sustainability, management extends beyond the provision of quantitative data alone. It depends on a range of related institutional, social, political, and economic systems

– referred to in this study as an 'enabling environment' [31–35]. While the term is more commonly used in participatory governance to assess the conditions for participation in water and sanitation [31,36], this study applies it more broadly to encompass the systemic and structural interdependencies that shape the viability of groundwater monitoring and management [33]. Beyond technical considerations, the effectiveness of groundwater monitoring systems is also shaped by how monitoring data are accessed, valued, and used within decision-making processes. Understanding these multidisciplinary relationships and perspectives on groundwater is critical for policy makers and managers, particularly in the context of climate uncertainty [34,37,38].

Persistent groundwater data scarcity is widely reported across many low- and middle-income settings, where monitoring networks face constraints relating to institutional coordination, resourcing, and long-term system performance [39]. While the severity and expression of these challenges vary by context, they are particularly prominent in countries such as Malawi - a highly groundwater dependent country under pressure from climate and demand changes with a stressed enabling environment [40,41].

1.3. Malawi, groundwater and data scarcity

In Malawi, approximately 65% of the population is directly dependent on groundwater for domestic drinking water [3]. The main aquifer types comprise of fractured and weathered basement rock units as well as alluvial deposits [42,43]. Despite its importance to Malawi's domestic drinking water supply and agricultural industry, functional access to groundwater monitoring data is severely limited [25,29]. This data scarcity is compounded by a monitoring network burdened with long-standing operational challenges [44,45]. A government-led inventory of the monitoring network in 2022 evidenced that of 106 groundwater monitoring stations visited, only six were equipped with data loggers that were in working condition [45].

In the absence of access to functional long-term groundwater level records, the scope for robust hydrogeological analysis, modelling, and interpretation remains constrained. As such, there have been repeated calls to improve the groundwater monitoring network's operation in Malawi, as in the wider SSA region, from government, academia, policymakers and international partners for several decades. Historically, emphasis has been placed on physical and technological infrastructure for network operation [45–48]. Yet despite investment into network expansion and equipment provision, progress has been limited in operationalising the network [44,45]. This raises questions of whether operationalising the monitoring network and addressing data scarcity represent a more deeply embedded and complex challenge. It also raises questions about whether investment should prioritise system strengthening initiatives over technological solutions to ensure progress is made.

Within Malawi, the importance of groundwater monitoring is explicitly recognised in national policy and planning frameworks. This is articulated in the 2023 National Water Policy which highlights the need to "ensure that systems for monitoring groundwater resources are put in place and are functional" [49]. However, although the policy provides a clear recognition and ambition, there remains a gap between policy ambition and clear guidance on the practical steps needed to achieve it. This gap provides a demand-led motivation for this study.

1.4. Research aim and approach

There is limited published documentation on Malawi groundwater monitoring network or on the specifics regarding its operation or data outputs. This research therefore explores groundwater data scarcity in Malawi by considering the operational and contextual factors that influence the performance of the national groundwater level monitoring network alongside the influence of the enabling environment. Using an inclusive and transdisciplinary co-creation process, this study aimed to investigate the persistent barriers limiting the groundwater level monitoring network's operation and identify opportunities for improvement.

2. Methodology

2.1. Ethics statement

The research design was subject to a two-stage ethics review and approvals process. The research protocol was first reviewed and approved by the Departmental Ethics Committee of the Department of Civil and Environmental Engineering at the University of Strathclyde. The study was subsequently reviewed and approved by Malawi's National Commission for Science and Technology (NCST), Committee on Research in the Social Sciences and Humanities (Protocol Nos. P.02/23/732 and P.05/24/873).

In accordance with the approved ethics protocols, participant information sheets were provided in advance of each workshop. Informed verbal consent was obtained from all participants at the start of each workshop session, in accordance with approved protocol. Verbal consent of participants was witnessed by the author and at least two other members of the authorship team during the workshops. Participants were informed of the voluntary nature of their involvement and their right to withdraw at any time without consequence.

2.2. Study design

Reflecting a co-creation and participatory research approach, this study adopted qualitative and exploratory research methods with stakeholders involved in groundwater monitoring [50–52]. Given the limited published literature on Malawi's groundwater monitoring network, primary data was required for this study (Fig 1). An initial scoping phase collected and analysed grey literature to establish a baseline understanding of the historical and institutional context. This phase informed the design of subsequent research activities, which included a series of workshops held in Malawi between February and March 2024. The workshops supported inclusive discussions on the causes of data scarcity, drawing on participatory and co-creation methods that support diverse perspectives from multiple stakeholder groups [51–54]. While the grey literature offered useful technical and institutional insights, it often reflected narrow viewpoints. The workshops were therefore used as a strategy to broaden collective understanding of how the groundwater monitoring network operates in practice and within the enabling environment [52]. Although co-creation was central to the approach taken, the study did not evaluate the co-creation process itself. Co-creation was used as a tool to bring together different forms of knowledge and to facilitate discussion between those directly involved or affected by groundwater monitoring [54,55].

2.3. Study area

Malawi is located in Sub-Saharan Africa with a population of over 20 million people, predominantly (84%) distributed in rural settings [57]. In these settings up to 82% of the population are directly reliant on groundwater for their drinking water [48], much of this supplied through communal handpumps. These handpumps have long been vulnerable to water supply challenges associated with physical factors and abrupt changes in the availability and safety of water provision [58,59]. In recent decades there has been a sharp increase in the number of supply boreholes drilled and fitted with handpumps, mainly financed through Official Development Assistance (ODA) or the Government of Malawi [59,60]. However, this expansion has not been matched with investment in the groundwater assessment and monitoring systems.

Groundwater management's importance is further underscored by Malawi's development strategy, the Malawi 2063 Vision, initiated in 2020 [61]. This strategy is centred around three key pillars: Agricultural Productivity and Commercialisation, Industrialisation, and Urbanisation. These pillars may pose a risk to groundwater quantity and quality if not carefully managed.

Malawi's high groundwater dependence combined with increasing water demands and uncertain impacts of climate change [8] raises an immediate challenge for policymakers. The socio-environmental and economic pressures in Malawi [62] characterise the enabling environment and make Malawi an important and globally relevant country in which to situate this study.

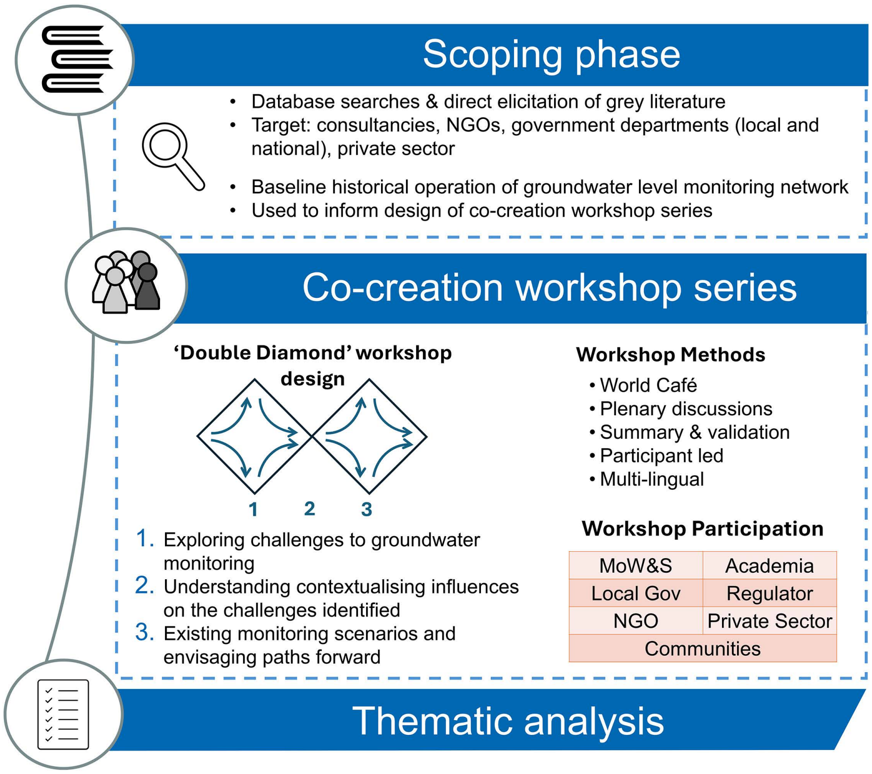

Fig 1. An illustrative summary of the research design and methodological tools used in this study. The figure highlights two major undertakings (1) Scoping phase (2023-24) and (2) a co-creation workshop series held in Malawi in February-March 2024. Workshop participants include Ministry of Water and Sanitation (MoWS), academia, local government officials (Local Gov), regulators, representatives from non-governmental organisations (NGO), the private sector and communities. The results of these are together presented as a thematic analysis. In total, three workshops were held in Malawi based on an adaptation of the 'double diamond' design process [56].

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2.4. Scoping phase

To complement the limited academic literature, a scoping phase was undertaken to gather relevant grey literature (Fig 1). Literature was drawn from general search engines and sector-specific databases, such as the Rural Water Supply Network's resources library [63]. In addition, information was obtained by directly contacting non-governmental organisations (NGOs), consultancies, government departments, and private sector actors in Malawi with known interests in groundwater. This process took place over several months between 2023 and 2024 by email, telephone and in-person office visits.

The collected literature was limited, but insightful, and was initially analysed by the lead author using reflexive thematic analysis [64,65] to develop a set of sensitising themes that were used to frame initial workshop discussions outlined below.

2.5. Workshop series

Three half-day workshops were held in Malawi over a four-week period between February and March 2024. Workshop development incorporated principles of participatory research and co-creation [52–54]. Using an adaptation of the 'double diamond' design process [56], workshops were sequentially structured to (1) Identify challenges to the groundwater level monitoring network, (2) Understand the contextualising influences on the identified challenges and explore steps to address them, (3) Establish a common understanding of existing water monitoring scenarios and envisage paths forward.

Each workshop began with a researcher-led presentation covering the research background and, where relevant, the preceding workshop content. After introductions and ice-breaking activities, the participants were divided into mixed background groups for breakout discussions. In the first workshop these discussions were based on the themes identified from the scoping phase [64]. Each group had a facilitator, and a World Café methodology [51] was used to facilitate discussion and to encourage mixing of participant views, manage power dynamics and experiences, and enhance the benefits to research participants [51,66]. At the end of each breakout session a plenary discussion session was held. Participants were able to discuss in either English or Chichewa (the two main national languages of Malawi) – with notes and records being kept in English.

Across the three workshops sessions a total of 50 participants attended with 16 attending multiple (>1) sessions and 7 attending all sessions. Participants were drawn from across the water sector in Malawi (Fig 1), including those with lived experience of rural water supply and users, recognising the benefit of diverse voices in co-creation process [51,54]. Initial recruitment of participants was drawn from the organisations and individuals identified in the scoping literature search, this was followed by snowballing recruitment and recommendations with the aim to have a non-numbers limited, wide ranging and diverse set of participants. The collection of participant groups had not previously been brought together for this purpose.

Workshop data was recorded in the form of written notes and comments as well as short reflective summaries by workshop rapporteurs. Notes were consolidated immediately after each session by facilitators/rapporteurs. The data was then subject to a rapid framework analysis [67]. An inductive/deductive thematic analysis was conducted [65], the themes were summarised and presented with examples at the subsequent workshop for further discussion and validation by the participants (Fig 1).

3. Results

3.1. Impacts and identified causes of data scarcity

Prior studies have highlighted the negative impact of groundwater data scarcity on scientific research and water policy development within SSA and in Malawi specifically [68,69].

In the workshops, participants expanded on the consequences of data scarcity, noting that decision-making within government and donor-funded water projects often rely on incomplete or inconsistent groundwater data, and sometimes no data at all. Participants underscored the urgency for addressing these issues in the short-term, given the increasing promotion of groundwater fed irrigation schemes [70] and the influence of climate change [8].

Overall, participants described the scarcity of groundwater data as restricting decision-makers capability to make strategic decisions on water management [29,71], and undermining long-term water security and resilience, and progress towards SDG 6 [29,39]. While this study and others highlight data scarcity challenges in groundwater level monitoring in Malawi and the broader SSA region [19,24,25,29], participants noted that few-to-no investigations have examined underlying reasons for these challenges or explored ways to address them.

To contextualise data scarcity, participants described how the groundwater level monitoring network currently operates in Malawi. They identified multiple challenges across different stages of the data management cycle (Fig 2). While generating data was a prominent challenge, particularly with non-functional equipment and vandalism of monitoring wells [44,72,73] elements of transferring, processing, using and managing groundwater level data were also discussed as issues that required attention (Fig 2).

Participants highlighted that addressing this challenge requires multiple actions and that there was no 'silver bullet' solution through technology provision or financing alone, which has often been prioritised by development donors. Discussions also noted that tackling individual challenges along the data cycle in isolation (Fig 2) would likely not resolve data scarcity issues. Instead, approaches must deliberately engage with the 'messy' institutional, governance, and community contexts in which groundwater data systems are embedded, the enabling environment, by design [74].

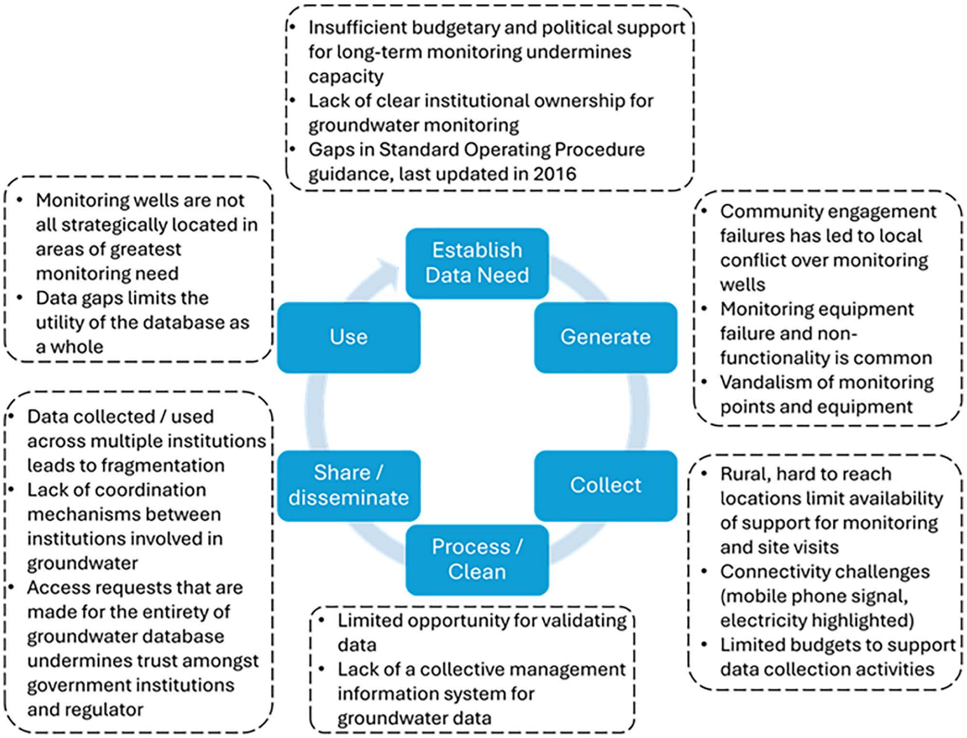

Fig 2. Figure presents participant-identified challenges which are associated with persistent groundwater data scarcity in Malawi. The challenges are presented alongside the different stages of a typical data management cycle to highlight participant reflections that challenges exist beyond just the data-generation stage, extending to how groundwater data are transferred, interpreted and used.

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3.2. Underlying coordination and governance challenges

Participants highlighted governance arrangements as a key factor of the enabling environment, shaping the operation of the groundwater level monitoring network. Challenges relating to coordination, guidance and institutional ownership of groundwater level monitoring were raised consistently across all three workshops Grey literature collected in the scoping phase helped contextualise these discussions and revealed inconsistencies across groundwater actors regarding the number and location of Malawi's monitoring wells [44,49,72,73,75] (Table 1).

Malawi's modern groundwater monitoring network was established in 2009 with a total of 35 monitoring wells across the country [25,72], expanded through the project-based groundwater exploration wells [72]. Participants noted that these inconsistencies reflect a lack of coordination between the multiple governmental institutions and non-state actors with roles in groundwater monitoring (Table 2). Participants also noted that legislative changes, such as the Water Resources Act 2013, which established regulatory authority [76], and the subsequent ministerial reorganisations following political elections, have contributed to complex and sometimes fragmented governance structures for water monitoring activities.

Participants discussed the practical coordination challenges in more detail. At the time of discussion, the Ministry of Water and Sanitation (MoWS) was described as often relying on the staff and resources of district-level government, particularly those within the District Councils to support groundwater monitoring activities reflecting earlier moves toward decentralised rural water-supply management in the 1990s and 2000s. [59,77].

However, because water-resource management has not been fully devolved financially, districts lack dedicated budgets and established posts for groundwater monitoring [78]. This has resulted in ad-hoc arrangements in which District Water

Table 1. A timeline constructed from grey literature sources to highlight the inconsistent reporting of monitoring wells in Malawi's national groundwater level monitoring network through time.

Year	Number of monitoring wells	Source
2009	35	National Water Resources Authority [72]
2017	85	ND WASH Consultants [44]
2022	106	Department of Water Resources, BASEflow, BAWI consultants [73]
2022	71	Kalin et al. [75]
2023	83	Department of Water Resources & National Water Resources Authority [72]
2023	71	Ministry of Water and Sanitation (MoWS) [49]

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Table 2. Institutions and actors which have an influence on Malawi's groundwater monitoring network. Roles within the network were identified and described by workshop participants.

Institution/ Group	Role(s) within groundwater monitoring network
Ministry of Water and Sanitation (Government of Malawi) (MoWS)	Current policy holder for groundwater and groundwater monitoring. Multiple divisions with an interest in groundwater including divisions of water resources, water quality and water supply. They provide central governance of the water sector. A source of water sector funding and leadership.
National Water Resources Authority (NWRA)	National regulator for water resources, with a mandate for managing and monitoring water resources. Recently operationalised after being established in 2013 [76].
Drillers	Group of service providers within the water sector. Drill and install groundwater wells, both for supply and monitoring. Generate groundwater data relevant to assessment and monitoring of groundwater, although this data is not routinely shared despite being required under the Water Resources Act 2013 [76].
Water Boards	Service provider for water supply, primarily in urban areas. Water boards monitor water resources as part of their planning activities.
Local Government and District Councils	Provide a local government staff presence at district level, including with specialist water officers. They provide district level resources (financial and capacity) as well as project limited funding which can be used to support activities of others. Provide local government knowledge and oversight of groundwater related activities (e.g., drilling).
NGOs	Multiple roles within groundwater; service provider to government bodies, funders, groundwater development and/or management, data collectors. They have an important role in independent advocacy and lobbying for groundwater management.
Donors and Development Partners	Provide sector wide funding in support of government and NGOs, financial capacity typically exceeds that of government. They have the potential to set priorities and influence national policy. Have not historically prioritised groundwater assessment or monitoring activities instead focussing on water supply.
Communities and local level actors (e.g., school staff)	Host to monitoring infrastructure within community (either public or privately held land), particularly in rural locations. Participation in some monitoring activities and in supporting roles, examples discussed included community members volunteering as monitoring well custodians or gauge readers.

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Offices rely on available staff, such as Water Monitoring Assistants, office guards or even teachers and Health Surveillance Assistants, to carry out monitoring.

Without a direct line of authority or a clear framework for cooperation between the MoWS and decentralised government, the use of district staff by the MoWS has had varied success. Historically, these arrangements have led to confusion and conflict between district councils and MoWS officials. Instances were described where district staff seconded to groundwater monitoring activities were reassigned by their district council without notifying MoWS, leading to interruptions in data collection and maintenance. Participants noted that flexibility of staff at district level could be an asset if well managed given challenges with budgeting and vacancy rates, estimated at between 35–40% [79]. With the recent operationalisation of the National Water Resources Authority (NWRA), coordination has become more complex, as new data flows from monitoring wells must now reach multiple national level actors. Fig 3 summarises this plurality of actors involved in the network and the associated data flows.

To address these issues, participants identified the need for a coordinating entity across institutions to simplify processes and reduce inefficiencies. An example of inefficiencies included the duplication of site visits whereby groundwater quality and groundwater levels (quantity) occur independently. Given the financial constraints within the water sector [62,80], reducing such duplication was seen as a key motivation for improving coordination. Participants also discussed the levels at which data is shared and consolidated. For example, while the MoWS and the NWRA reported exchanging information at national level, district-level staff expressed concern that this arrangement required them to submit slightly different versions of the same data to multiple offices including the District Council – without gaining access to a consolidated dataset for their own use.

Improved coordination among non-government actors, many of which generate or utilise groundwater level data, was also a priority (Table 2). Ongoing reviews of the Waterworks Act (1995) [81] and the Water Resources Act (2013) [76] were highlighted as an opportunity to clarify and address this area of need.

Underpinning these complex institutional arrangements is a lack of available finance within Malawi's water sector. Often discussed as part of broader Water, Sanitation and Hygiene (WASH) finance strategies, the sector faces a persistent funding gap [62,80]. While estimates of this gap vary [80,82], there is a recognised need to prioritise cost-effective investments and improve coordination across sectors [41].

Workshop participants highlighted how financial constraints and human capacity limitations hinder groundwater level monitoring activities.

Funding shortfalls affect all aspects of the monitoring network, from planning and maintenance of infrastructure to routine collection and analysis of data (Fig 2). A lack of political-level support for monitoring activities was highlighted as a key reason for funding shortfalls – both within government and development partners. Monitoring was discussed as having long-term value to society, which may not align with short-term political or donor objectives [41,62]. As such, participants observed how finance in the WASH sector tends to be prioritised to water development projects rather than assessment or monitoring needs and resources.

To address funding shortfalls, participants identified two major areas of focus: (1) advocacy and generating funding support, and (2) working efficiently within current resource constraints:

1. Advocacy work for funding support: participants emphasised the need to link groundwater's importance to broader development agendas, such as the Malawi 2063 vision [61] and the UN SDGs, particularly the role of groundwater in economic development and adaptation to climate change [10]. Re-establishing a national groundwater forum with regular meetings was considered an appropriate forum to further these discussions.

2. Working within funding constraints: Participants stressed that advocacy alone was not viable due to the urgency of groundwater data needs. They highlighted that the value of exploring groundwater monitoring methods which were not reliant on large external investments should be an area for further research investigation.

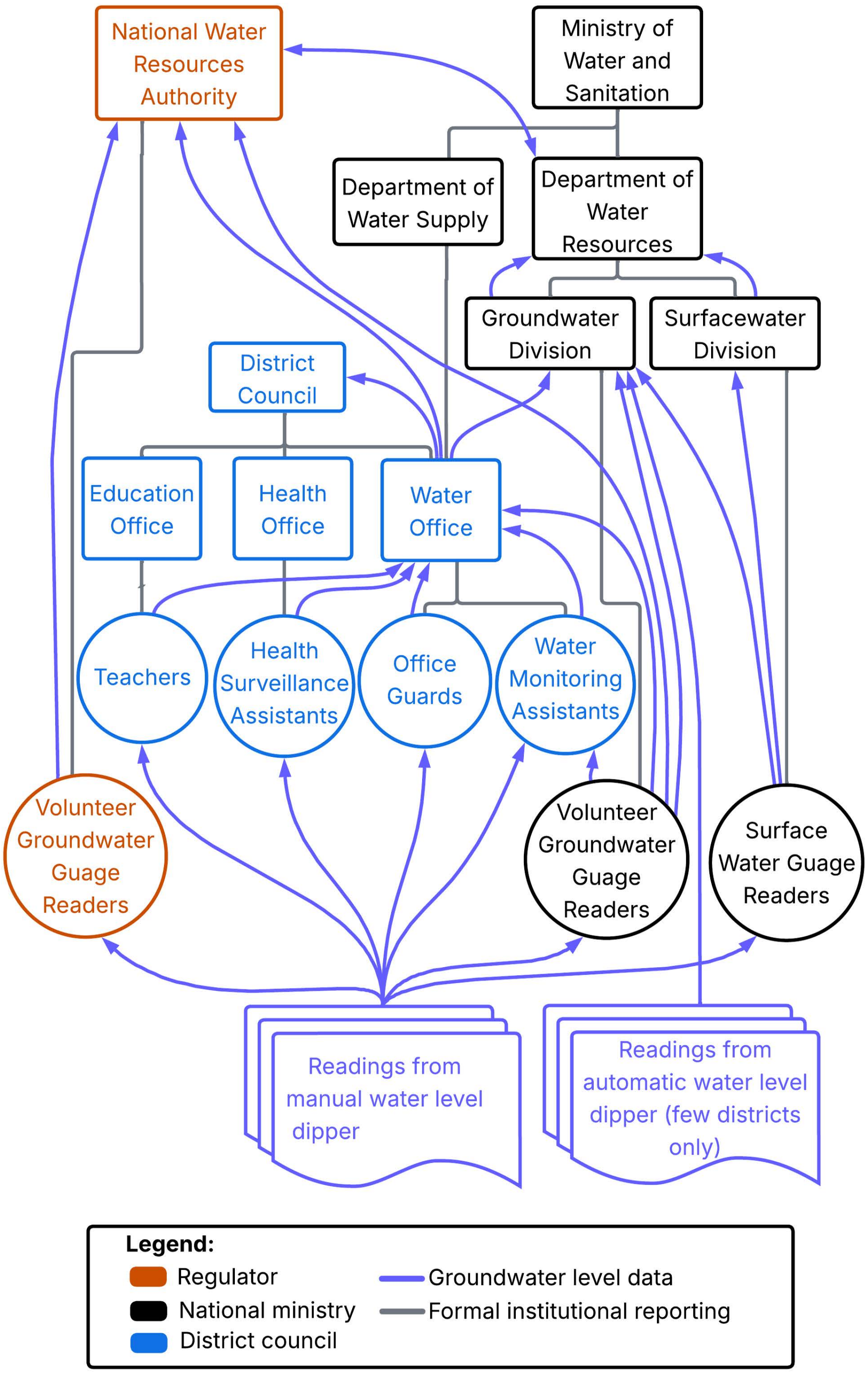

Fig 3. A diagram of the groundwater level monitoring network as it currently operates in Malawi, as described by workshop participants. The diagram highlights both groundwater level data pathways (blue) and the formal institutional reporting relationships (grey) Participants noted that these two flows are not aligned within policy or practice.

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The institutional barriers outlined here not only affect strategic level coordination of the monitoring network but also how groundwater monitoring is implemented on the ground, particularly in how communities are engaged. As such, community-level engagement emerged as both a consequence of upstream governance issues and a critical influence on the performance of the network.

3.3. The role of community engagement

Community engagement featured prominently across all workshop sessions, influencing several stages of the groundwater data cycle (Fig 2). In particular, the relationship between local communities living near monitoring wells and vandalism was actively and intensively discussed as a key challenge. Participants used the term, 'community' broadly to refer to the local people and structures that exist in proximity to a monitoring well, recognising the variable meaning in WASH contexts [83]. The role of communities was significant enough to warrant participants describing them as having an "institutional importance" (Table 2).

While improving community engagement was seen as a challenge it was also described as an opportunity, where knowledge and lived experience from within Malawi's WASH sector could be repurposed to the benefit of groundwater.

The poor physical condition of the monitoring wells was consistently referenced in the grey literature with damage often preventing data collection. [44,72,75]. Chronic physical infrastructure challenges such as crumbling/broken civil works, broken locks, and damaged or missing equipment was commonly attributed to vandalism from nearby communities [44,45,72], and suggests a potential reason why the number of monitoring wells in the national network may vary year-on-year (Table 1). Although vandalism is also a challenge in water supply systems in Malawi [84], and in monitoring settings elsewhere [85], the grey literature reviewed presents vandalism as a root cause of the infrastructure challenges without any further investigation or explanation.

Workshop discussions added greater nuance, highlighting that community interactions with monitoring infrastructure are not always deliberately adversarial. Participants described cases where 'vandalism' resulted from miscommunication or misunderstanding. For example, a sub-contracted borehole driller on a groundwater monitoring well installation reportedly incorrectly told the local community they were installing a well for drinking water supply, when the well was sealed and locked, members of the local community were distressed and damaged the structure. Another example involved the installation of monitoring wells in location without functioning water supply, leading to conflict. Participants noted that these issues stem from a lack of informed or formalised procedure and process for engaging communities. Overall, examples indicate that behaviour framed as 'vandalism' in grey literature is often reflective of a wider failure of governance systems.

Developing a clearer community engagement strategy for monitoring activities was therefore identified as an important preventative measure to reduce conflict and improve relationships with local communities situated near monitoring infrastructure.

The value of community engagement in monitoring activities has been explored through citizen science across several disciplines [86,87]. Participants noted that volunteer gauge readers from local communities have occasionally been used to help collect groundwater level data with mixed success (Fig 3). While not explicitly referring to this as citizen science these practices broadly align with standard definitions [88,89].

Participants described the important role that communities play in the operation of the monitoring network. Communities 'host' monitoring wells and are typically responsible for the general upkeep and safety of the wells and equipment – particularly in remote areas. However, this custodian role is informal, lacks any official recognition or support, and is rarely reflected in formal planning or procedural discussions.

When discussing the role of communities taking groundwater measurements, participants noted that the relative simplicity of groundwater levels makes them more feasible than other measurements such as water quality. However, not all participants agreed, expressing concerns about maintaining data quality and further fragmenting an already complex monitoring system by incorporating volunteers. Participants identified a need for further research into citizen science informed monitoring approaches including consideration of wider participatory challenges and opportunities and expanding the use and impact of data beyond central agencies.

3.4. Institutional procedures and technical challenges

A series of Standard Operating Procedures (SOPs) were published by the then Ministry of Agriculture, Irrigation & Water Development in 2016 [90–93], the most recent official guidance on groundwater monitoring and related activities. However, participants reported limited knowledge of the existing SOPs, and noted that given the data scarcity challenges, they require review.

While the SOPs provide technical drilling guidance [92], they information on the strategic design or intended purpose of the network including information such as where wells should be situated, what management questions the data are intended to answer, and who the data should be made accessible to. Participants highlighted that several areas of hydrogeological interest, such as nearby groundwater-fed irrigation schemes, were not currently covered by the monitoring network. With increasing demand for groundwater in Malawi, and with changing climatic patterns, participants identified a need to define the groundwater monitoring strategy to maximise impact and efficiency. Although supporting work has already been undertaken in the literature to characterise groundwater across the region [3,4], grey literature collected does not specifically mention the design intention of Malawi's current monitoring network. Nevertheless, participant discussions suggested that a combination of funding prioritisation, political/ institutional complexity, and technical challenges have all been influential in the resulting network design, sometimes superseding hydrogeological need. This re-highlights longstanding barriers and the complexity of groundwater monitoring [94].

Technical challenges such as limited physical access to monitoring sites and provision of basic services (e.g., electricity, internet access) were noted as significant barriers to groundwater monitoring (Fig 2). However, these challenges are not reflected in the current SOPs, leaving practitioners to use improvised or ad-hoc solutions or to overlook key complexities entirely. This results in weakening institutional coordination.

As an example, the SOPs refer to a Microsoft Excel based system for groundwater database management [91], yet participants did not reference this system in any of the workshop discussions. Instead, "WhatsApp" was discussed as the most frequently used method to transfer and store groundwater data, particularly for monitoring wells located in very rural and hard to reach locations. While an informal tool, the use of "WhatsApp" highlights adaptive workarounds to practical and ongoing challenges.

Participants also highlighted constraints related to technological solutions, such as unreliable electricity and mobile telecommunication connectivity have undermined previous monitoring investments. An example of this was telemetric monitoring equipment installed at remote monitoring sites, which were vulnerable to vandalism and/or disruptions related to the enabling environment (e.g., electricity loss, maintenance visits, mobile signal).

4. Discussion

4.1. Operational challenges in groundwater level monitoring

Throughout the study, participants described a range of technical, institutional, financial, and social challenges. These were highlighted not as isolated issues but interconnected parts of the groundwater system, linking the day-to-day monitoring operations to the wider enabling environment.

A range of operational barriers to Malawi's monitoring network such as vandalism, equipment failure, and limited community engagement were prominent in both the collected grey literature and workshops. However, while the grey literature implies that these barriers are isolated operational hurdles [44,72,73], this research highlights them as interconnected symptoms of underlying systemic challenges within the enabling environment. For vandalism in particular, participants linked damage to miscommunication, unclear responsibility and limited local engagement, rather than deliberate obstruction alone. This interpretation aligns with similar observations raised in regional studies [39]. These insights suggest that infrastructure investment alone will remain vulnerable to challenges unless embedded within clear, inclusive and holistic improvement strategies. Future monitoring strategies, in any context, must therefore consider not only the technical requirements but also the local social and governance dynamics of each monitoring site before any installation is undertaken. In particular, the introduction of clear community-level prerequisites, such as a functioning water supply, will help establish minimum viable enabling conditions and this should be reflected in updated SOPs.

This failure to invest in the wider enabling environment has led to systemic operational constraints. However, there were examples of adaptive workarounds, such as the use of 'WhatsApp' to transmit groundwater data, or the use of non-groundwater professionals to collect data. Although these were seen as pragmatic and inventive responses, these can only provide support short-term solutions if not effectively embedded, and pose challenges for data integrity, consolidation and process standardisation in the longer term. Advancing the operation of the monitoring network must harness adaptability and flexibility shown by stakeholders but also provide structure to promote the quality and usability of data.

In totality, the results presented in this study suggests that technical interventions alone are insufficient to solve the range of operational challenges affecting the monitoring network. Instead, they show that the influence of the enabling environment has been historically underestimated by political and donor-driven priorities, to the detriment of its operational sustainability. Importantly, participants and grey literature evidence highlighted that the absence of long-term, uninterrupted groundwater level records limits the feasibility of meaningful quantitative analysis and hydrogeological assessment at scale. Improving monitoring operations, and addressing data scarcity, will therefore require better appreciation for the relationship between behaviour, infrastructure, and institutional processes and involve greater focus on governance. We acknowledge that while specific institutional conditions shaping data scarcity are context dependent, the resulting challenges are reported across many data-limited groundwater monitoring systems [33,34] and speak towards generalisable improvements in how monitoring is operationalised and considered in water governance frameworks.

4.2. Structural and systemic barriers in the enabling environment

The enabling environment for groundwater monitoring in Malawi is shaped by institutional fragmentation, procedural ambiguity, and under-resourcing. This is reinforced by ongoing misalignment between practical groundwater data pathways and formal reporting relationships (Fig 3), creating responsibility gaps and weakening accountability for data continuity. In Malawi, as in other settings, these systemic barriers constrain not only the sustainability of monitoring systems but also their relevance to decision-makers. Despite groundwater's importance to climate resilience and water security, implementation and prioritisation of groundwater remains under prioritised and underfunded by political and donor-level actors [80] – a phenomenon not unique to Malawi [23].

A consistent concern was how blurred mandates across institutions, particularly between national agencies and decentralised district offices, create unintentional accountability gaps, delay data flows and transfers, and undermine coordination. In the absence of enforced standard operating procedures (SOPs), informal practices have emerged as adaptive coping mechanisms which lack consistency and oversight. This is compounded by limited guidance on the network's strategic purpose this absence is significant because groundwater monitoring should support more than data generation alone and connect directly to decision-making needs. For long-term monitoring of groundwater levels this could include developing understanding of how groundwater systems respond to land-use change, climate variability and long-term recharge and abstraction. The inconsistent reporting of monitoring well numbers and status over time (Table 1) further suggests fragmented oversight and limited institutional memory. This mirrors dynamics observed across other data-scarce regions, where the gap between recognising groundwater's importance and weak operational prioritisation of groundwater has hindered the operation of monitoring systems [39]. Deeper integration of groundwater monitoring needs into other sectors is required. Even when political will exists, budget lines remain unstable and staff turnover or vacancy disrupts continuity, highlighting a need for the implementation of 'good governance' [33,35].

The study also highlights the important yet often overlooked role of communities in supporting monitoring activities in Malawi. Participants described communities as both a cause of challenge (through vandalism or conflict) and as a valuable source of local knowledge and supporting resource. It was emphasised that a need to account for community roles in formal guidance, as well as a willingness to explore mechanisms for their continued engagement through citizen science type engagements in the future.

Notably, participants highlighted a donor-driven preference for tangible, technical investments, such as infrastructure provision and network expansion, over the more complex work of governance reform [74]. This tendency has contributed to a monitoring system shaped as much by funding priorities and institutional complexity as by the technical hydrogeological needs. The resulting tension between short-term incentives and long-term requirements reflect a fragile enabling environment in which coordination is difficult and monitoring remains deprioritised [35]. This aligns with broader debates within the WASH sector about the preferential measurement of short-term outcomes [95]. Addressing short-termism and projectisation is critical for long-term water security and resilience [10,96]. Decision makers in Malawi, as elsewhere, should seek to rectify this in implementation of long-term development visions such as the Malawi 2063 vision [61,70] and a strong starting point would be the articulation of a strategic groundwater monitoring plan with clear, targeted purposes for different functions.

Taken together, these findings help to explain the disconnect between the formal recognition of groundwater monitoring within policy frameworks [49,90] and the practical challenges of implementing and sustaining monitoring systems on the ground. While groundwater is acknowledged as central to climate resilience [8,10] and to Malawi's development vision, this recognition has not consistently been matched by the operational support, technical guidance, institutional coordination, and long-term financing needed to translate ambition into practice. As highlighted by participants, addressing groundwater data scarcity will require more than recognition in policy documents, it demands sustained investment, clearer implementation pathways, and support structures, and government and non-governmental partnerships, that enable long-term function.

4.3. The value of co-creation process for identifying interconnected challenges

A strength of this study lies in its methodological approach. The co-creation process created a space for dialogue across institutional and societal backgrounds [37,66], bringing together stakeholders who had not previously engaged collectively on groundwater monitoring. The methodology helped foster mutual reflections and challenge dominant narratives, such as around vandalism of monitoring wells which, as in previous literature, would otherwise have gone unchallenged or interrogated.

Importantly, the process also enabled stakeholders to co-identify actions to address the challenges such as the need for clearer standard operating procedures, improved feedback and coordination between local and national actors, as well as more formalised mechanisms for community engagement. Participants also highlighted and were able to discuss appropriate forums for higher level advocacy, particularly funding, such as reconstituting the national groundwater forum, which was held after the workshops in this study.

While citizen science was not the study's primary focus, participant interest in more adaptable and participatory monitoring approaches suggests an opportunity to broaden engagement with groundwater data and increase its visibility and relevance, provided such efforts are designed collaboratively and aligned with existing institutional arrangements. More broadly, this study reinforces international calls for participatory water governance [36,50]. In this context, supporting participation is relevant not only to data collection but also to clarifying the hydrogeological questions monitoring should answer and how information is communicated between decision makers and those on the ground.

These insights are transferable to other settings and offer value in shaping how groundwater monitoring challenges are understood and approached, cautioning against prescriptive technocratic solutions without engagement. From this perspective, the place-based and co-creative nature of the research should be viewed as a strength. The process was able to surface contextual constraints and enabling conditions that are often obscured in technical or formal reporting mechanisms – such as in the grey literature.

4.4. Limitations of the study

While the workshop series involved 50 participants from across Malawi's water sector, only 7 participants attended all three sessions and 16 attended more than one. This variation in attendance across workshop sessions may have influenced the continuity of discussions but it also introduced new perspectives at each stage of the process, which served to help validate earlier insights.

The study was delivered within a limited time and resource window, which limited the ability to conduct any follow-up engagements. We note the time-consuming nature of transdisciplinary research and highlight that while aspects of planning and conducting a data-collection process such as this one is difficult, the benefits in terms of insights are unmatched through other methods. There is a low availability of published literature specifically addressing Malawi's groundwater monitoring network – a gap this paper addresses – but this limits the ability to compare and contextualise some findings, it also reflects the novelty and contribution of this study.

Finally, the study did not seek to evaluate the co-creation process itself, nor was qualitative data from the workshops recorded. Future work should consider developing the methodology to have the ability to capture direct quotes from participants to enhance richness of discussion [51] as well as to evaluate the co-creation process itself as experienced by participants.

5. Conclusions

Despite formal recognition of groundwater monitoring's importance within national policy, translating ambition into sustained, functional monitoring systems remains a key challenge. This study demonstrates that persistent groundwater data scarcity in Malawi is deeply rooted in systemic governance, procedural, and institutional challenges, rather than arising solely from technical or financial limitations. The interlinked constraints form part of a stressed enabling environment and cannot be addressed in isolation. Efforts to strengthen groundwater data systems, and to improve informed decision-making, therefore require holistic, context-sensitive strategies that go beyond policy recognition and instead explicitly account for strengthening institutions and clarifying both operational and decision-making processes as part of their design.

In response to the study aim, findings point to several priority areas for action in Malawi. These include firstly the need to develop institutional clarity around roles and responsibilities regarding groundwater monitoring, including a strategic articulation of the purpose and intended use of the monitoring network. Secondly the re-development of fit-for-purpose and context-appropriate operating procedures that define not only how data are collected, but how they should be interpreted, shared and used, and thirdly the establishment of sustainable financing mechanisms to support long-term monitoring and maintenance beyond projects. These actions will support national development priorities outlined in the Malawi 2063 vision. As such, addressing these foundational system and governance issues is essential if groundwater data are to meaningfully inform planning and management processes and to unlock the long-term, reliable datasets required for hydrogeological analysis. A failure to do so is likely to undermine future investments in monitoring infrastructure and in water security.

The co-creation process adopted in this study proved critical in revealing how high-level institutional and governance challenges translate into day-to-day monitoring challenges and contribute to persistent data gaps. By bringing together diverse stakeholders, the approach enabled shared reflection on both system weaknesses but also where there are opportunities to strengthen participation, ownership, and system sustainability. Future work in this field should seek to engage at all levels.

While much of the findings and recommendations are grounded in Malawi's specific institutional and hydrogeological setting, the broader contribution of this study lies in highlighting how groundwater data scarcity emerges from interconnected technical, institutional, and procedural conditions. These insights underscore the importance of place-based approaches for understanding and addressing monitoring challenges, particularly in data-limited settings where externally derived or standardised solutions are unlikely to be effective. At the same time, the underlying lesson that operational monitoring failures can be downstream consequences of governance, procedural and resourcing constraints may be relevant to other data-limited groundwater monitoring systems.

Looking ahead, further research is needed to explore how inclusive data generating and utilising approaches, such as citizen science initiatives, might complement formal monitoring systems and respond to local needs, particularly where capacity and resources are constrained. More broadly, strengthening groundwater monitoring should be understood not as a narrowly technical task, but as a strategic governance challenge. Further research and action are needed to incorporate this learning into national and international discussions about water governance in the era of rapid climate and population change.

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Author contributions

Conceptualization: Donald John Charles Robertson, Tracy Morse, Rowan Ellis, Christopher J. White, Muthi Nhlema, Given Ngwira, Zione Butao, Macpherson Nkhata.

Data curation: Donald John Charles Robertson.

Formal analysis: Donald John Charles Robertson.

Funding acquisition: Donald John Charles Robertson, Tracy Morse, Rowan Ellis, Christopher J. White.

Investigation: Donald John Charles Robertson, Sydney Byrns, Muthi Nhlema, Given Ngwira, Zione Butao, Mike Myaba, Macpherson Nkhata.

Methodology: Donald John Charles Robertson, Rowan Ellis.

Project administration: Donald John Charles Robertson.

Supervision: Tracy Morse, Rowan Ellis, Christopher J. White.

Validation: Donald John Charles Robertson.

Writing – original draft: Donald John Charles Robertson.

Writing – review & editing: Donald John Charles Robertson, Tracy Morse, Sydney Byrns, Rowan Ellis, Christopher J. White, Given Ngwira, Mike Myaba, Macpherson Nkhata.

References

1. Velis M, Conti KI, Biermann F. Groundwater and human development: synergies and trade-offs within the context of the sustainable development goals. Sustain Sci. 2017;12(6):1007–17. https://doi.org/10.1007/s11625-017-0490-9 PMID: 30147765
2. Guppy L, Uyttendaele P, Villholth KG, Smakhtin VU. Groundwater and sustainable development goals: analysis of interlinkages [Internet]. United Nations University Institute for Water, Environment and Health; 2018 [cited 2025 Jun 10]. Available from: https://hdl.handle.net/10568/99044

3. British Geological Survey [Internet]. Africa Groundwater Atlas. [cited 2025 Jun 3]. Available from: https://www.bgs.ac.uk/geology-projects/africa-groundwater-atlas/
4. Adelana S, Fantong W, Nedaw D, Duah A. Groundwater and Health: Meeting Unmet Needs in Sub-Saharan Africa. In: Jones JAA, editor. Sustaining Groundwater Resources: A Critical Element in the Global Water Crisis [Internet]. Dordrecht: Springer Netherlands. Springer Netherlands. 2011. pp. 21–33. https://doi.org/10.1007/978-90-481-3426-7_2
5. MacDonald AM, Calow RC. Developing groundwater for secure rural water supplies in Africa. Desalination. 2009;248(1–3):546–56. https://doi.org/10.1016/j.desal.2008.05.100
6. Cuthbert MO, Gleeson T, Moosdorf N, Befus KM, Schneider A, Hartmann J, et al. Global patterns and dynamics of climate–groundwater interactions. Nat Clim Change. 2019;9(2):137–41. https://doi.org/10.1038/s41558-018-0386-4
7. Cobbing J, Hiller B. Waking a sleeping giant: realizing the potential of groundwater in Sub-Saharan Africa. World Dev. 2019;122:597–613. https://doi.org/10.1016/j.worlddev.2019.06.024
8. Taylor RG, Scanlon B, Döll P, Rodell M, van Beek R, Wada Y, et al. Ground water and climate change. Nature Clim Change. 2012;3(4):322–9. https://doi.org/10.1038/nclimate1744
9. Lerner DN, Harris B. The relationship between land use and groundwater resources and quality. Land Use Policy. 2009;26:S265–73. https://doi.org/10.1016/j.landusepol.2009.09.005
10. Robertson DJ, MacAllister DJ, Gurmessa SK, Matta J, MacDonald A, McManus C, et al. Groundwater must be fully integrated into WASH programmes to make them climate resilient. PLOS Water. 2025;4(7):e0000404. https://doi.org/10.1371/journal.pwat.0000404
11. United Nations University [Internet]. Global Water Bankruptcy. [cited 2026 Jan 30]. Available from: https://unu.edu/inweh/collection/global-water-bankruptcy
12. Jasechko S, Seybold H, Perrone D, Fan Y, Shamsudduha M, Taylor RG, et al. Rapid groundwater decline and some cases of recovery in aquifers globally. Nature. 2024;625(7996):715–21. https://doi.org/10.1038/s41586-023-06879-8 PMID: 38267682
13. Bilal H, Govindan R, Al-Ansari T. Investigation of groundwater depletion in the state of Qatar and its implication to energy water and food nexus. Water. 2021;13(18):18. https://doi.org/10.3390/w13182464
14. MacAllister DJ. Groundwater decline is global but not universal. Nature. 2024;625(7996):668–70. https://doi.org/10.1038/d41586-024-00070-3 PMID: 38267676
15. MacDonald AM, Lark RM, Taylor RG, Abiye T, Fallas HC, Favreau G. Mapping groundwater recharge in Africa from ground observations and implications for water security. Environ Res Lett. 2021;16(3):034012. https://doi.org/10.1088/1748-9326/abd661
16. Schilling J, Hertig E, Tramblay Y, Scheffran J. Climate change vulnerability, water resources and social implications in North Africa. Reg Environ Change. 2020;20(1). https://doi.org/10.1007/s10113-020-01597-7
17. Nick Robins NR, Jeff Davies JD, Philip Hankin PH, Dieter Sauer DS. Groundwater and data - an African experience. Waterlines. 2003;21(4):19–21. https://doi.org/10.3362/0262-8104.2003.022
18. Scanlon BR, Fakhreddine S, Rateb A, de Graaf I, Famiglietti J, Gleeson T. Global water resources and the role of groundwater in a resilient water future. Nat Rev Earth Environ. 2023;4(2):87–101. https://doi.org/10.1038/s43017-022-00378-6
19. United Nations. The United Nations World Water Development Report 2024: Water for Prosperity and Peace. Paris: UNESCO; 2024.
20. Condon LE, Kollet S, Bierkens MFP, Fogg GE, Maxwell RM, Hill MC. Global groundwater modeling and monitoring: opportunities and challenges. Water Resour Res. 2021;57(12). https://doi.org/10.1029/2020WR029500
21. Braune E, Xu Y. Groundwater management issues in Southern Africa – An IWRM perspective. WSA. 2019;34(6):699. https://doi.org/10.4314/wsa.v34i6.183672
22. Braune E, Xu Y. The role of ground water in sub-Saharan Africa. Ground Water. 2010;48(2):229–38. https://doi.org/10.1111/j.1745-6584.2009.00557.x PMID: 19341372
23. United Nations. The United Nations World Water Development Report 2022: Groundwater Making the invisible visible. Paris: UNESCO; 2022.
24. World Bank. Malawi - Country Environmental Analysis. World Bank; 2019.
25. Rivett MO, Miller AVM, MacAllister DJ, Fallas A, Wanangwa GJ, Mleta P, et al. A conceptual model based framework for pragmatic groundwater-quality monitoring network design in the developing world: Application to the Chikwawa District, Malawi. Groundwater Sustain Dev. 2018;6:213–26. https://doi.org/10.1016/j.gsd.2018.01.005
26. Van De Giesen N, Hut R, Selker J. The Trans-African Hydro-Meteorological Observatory (TAHMO). WIREs Water. 2014;1(4):341–8. https://doi.org/10.1002/wat2.1034
27. Gorgoglione A, Castro A, Chreties C, Etcheverry L. Overcoming data scarcity in earth science. Data. 2020;5(1):1. https://doi.org/10.3390/data5010005
28. Chen L, Xu J, Wang G, Liu H, Zhai L, Li S, et al. Influence of rainfall data scarcity on non-point source pollution prediction: Implications for physically based models. J Hydro. 2018;562:1–16. https://doi.org/10.1016/j.jhydrol.2018.04.044
29. Fraser CM, Kalin RM, Kanjaye M, Uka Z. A national border-based assessment of Malawi's transboundary aquifer units: Towards achieving sustainable development goal 6.5.2. J Hydrol: Region Stud. 2020;31:100726. https://doi.org/10.1016/j.ejrh.2020.100726

30. Zuffinetti G, Meunier S, Hudelot C, MacAllister DJ, Krishan G, Lutton E, et al. Large-scale modeling of solar water pumps using machine learning. Appl Energy. 2026;406:127268. https://doi.org/10.1016/j.apenergy.2025.127268
31. Jiménez A, LeDeunff H, Avello P, Scharp C. Enabling environment and water governance: a conceptual framework. Accountability for Sustainability Partnership; 2016.
32. Giordano M, Shah T. From IWRM back to integrated water resources management. Int J Water Resour Dev. 2014;30(3):364–76. https://doi.org/10.1080/07900627.2013.851521
33. Mukherji A, Shah T. Groundwater socio-ecology and governance: a review of institutions and policies in selected countries. Hydrogeol J. 2005;13(1):328–45. https://doi.org/10.1007/s10040-005-0434-9
34. Megdal SB. Invisible water: the importance of good groundwater governance and management. npj Clean Water. 2018;1(1). https://doi.org/10.1038/s41545-018-0015-9
35. de Chaisemartin M, Varady RG, Megdal SB, Conti KI, van der Gun J, Merla A. Addressing the Groundwater Governance Challenge. In: Karar E, editor. Freshwater Governance for the 21st Century. Cham: Springer International Publishing; 2017. pp. 205–27. https://doi.org/10.1007/978-3-319-43350-9_11
36. Jiménez A, LeDeunff H, Giné R, Sjödin J, Cronk R, Murad S, et al. The enabling environment for participation in water and sanitation: a conceptual framework. Water. 2019;11(2):2. https://doi.org/10.3390/w11020308
37. Lang DJ, Wiek A, Bergmann M, Stauffacher M, Martens P, Moll P. Transdisciplinary research in sustainability science: practice, principles, and challenges. Sustain Sci. 2012;7(1):25–43. https://doi.org/10.1007/s11625-011-0149-x
38. Kløve B, Ala-Aho P, Bertrand G, Gurdak JJ, Kupfersberger H, Kværner J, et al. Climate change impacts on groundwater and dependent ecosystems. J Hydrol. 2014;518:250–66. https://doi.org/10.1016/j.jhydrol.2013.06.037
39. Veness WA, Buytaert W. Towards an evidence base for groundwater data investments. Environ Sci Policy. 2025;164:104014. https://doi.org/10.1016/j.envsci.2025.104014
40. Chiluwe QW, Nkhata B. Analysis of water governance in Malawi: towards a favourable enabling environment? J Water Sanit Hyg Dev. 2014;4(2):313–23. https://doi.org/10.2166/washdev.2014.087
41. Akpabio EM, Mwathunga E, Rowan JS. Understanding the challenges governing Malawi's water, sanitation and hygiene sector. Int J Water Resour Dev. 2021;38(3):426–46. https://doi.org/10.1080/07900627.2021.1897947
42. Scheidegger J, Lafare A, Mansour MM. Malawi hydrogeological and water quality mapping: national scale recharge estimation [Internet]. 2019 [cited 2026 Jan 26]. Available from: https://nora.nerc.ac.uk/id/eprint/522918/
43. Robins N, Davies J, Farr J. Groundwater supply and demand from southern Africa's crystalline basement aquifer: evidence from Malawi. Hydrogeol J. 2013;21(4):905–17. https://doi.org/10.1007/s10040-013-0956-5
44. ND WASH Consultants. Situation analysis survey on groundwater resources monitoring system for Central, Northern and Southern regions and national consolidated summaries, in Malawi. Draft Final Report prepared for Japan International Cooperation Agency (JICA); 2017.
45. Ministry of Water and Sanitation, Department of Water Resources. Report on assessment of groundwater monitoring wells in Malawi. Lilongwe: Government of Malawi, Ministry of Water and Sanitation, Department of Water Resources; 2022.
46. Pietersen K, Beekman H. Position paper: Groundwater management in the southern African development community. SLR; 2016. https://doi.org/10.13140/RG.2.2.14696.06400
47. BASEflow. Proposal for revitalisation of the groundwater monitoring network in the Shire River and Lake Chilwa Basin. Blantyre: BASEflow;2023.
48. Sauramba J, Mkandawire T, Munyai B, Majiwa M. Groundwater policy, legal and institutional framework situation analysis: gaps and action plan: the case of Malawi. Groundwater for Sustainable Livelihoods and Equitable Growth. CRC Press; 2022.
49. Ministry of Water and Sanitation. National Water Policy. Lilongwe: Ministry of Water and Sanitation; 2023.
50. Cargo M, Mercer SL. The value and challenges of participatory research: strengthening its practice. Ann Rev Public Health. 2008;29(1):325–50. https://doi.org/10.1146/annurev.publhealth.29.091307.083824
51. Löhr K, Weinhardt M, Sieber S. The "World Café" as a participatory method for collecting qualitative data. Int J Qual Methods. 2020;19. https://doi.org/10.1177/1609406920916976
52. Nguyen NT, Collins A, Collins CM. Trends and patterns in the application of co-production, co-creation, and co-design methods in studies of green spaces: a systematic review. Environ Sci Policy. 2024;152:103642. https://doi.org/10.1016/j.envsci.2023.103642
53. Mugari E, Nethengwe NS, Gumbo AD. A co-design approach for stakeholder engagement and knowledge integration in flood risk management in Vhembe district, South Africa. Front Clim. 2025. https://doi.org/10.3389/fclim.2025.1517837
54. Vargas C, Whelan J, Brimblecombe J, Allender S. Co-creation, co-design, co-production for public health - a perspective on definition and distinctions. Public Health Res Pract. 2022;32(2):3222211. https://doi.org/10.17061/phrp3222211 PMID: 35702744
55. Raymond CM, Fazey I, Reed MS, Stringer LC, Robinson GM, Evely AC. Integrating local and scientific knowledge for environmental management. J Environ Manage. 2010;91(8):1766–77. https://doi.org/10.1016/j.jenvman.2010.03.023 PMID: 20413210
56. Ball J. The double diamond: A universally accepted depiction of the design process. Design Council; 2019. pp. 1.
57. 2018 Malawi Population and Housing Census: Main Report. Zomba: National Statistical Office; 2019.

58. MacAllister DJ, Nedaw D, Kebede S, Mkandawire T, Makuluni P, Shaba C, et al. Contribution of physical factors to handpump borehole functionality in Africa. Sci Total Environ. 2022;851(Pt 2):158343. https://doi.org/10.1016/j.scitotenv.2022.158343 PMID: 36041625
59. Truslove JP, V. M. Miller A, Mannix N, Nhlema M, Rivett MO, Coulson AB, et al. Understanding the Functionality and Burden on Decentralised Rural Water Supply: Influence of Millennium Development Goal 7c Coverage Targets. Water. 2019;11(3):494. https://doi.org/10.3390/w11030494
60. Chasukwa M, Banik D. Bypassing government: aid effectiveness and malawi's local development fund. PaG. 2019;7(2):103–16. https://doi.org/10.17645/pag.v7i2.1854
61. National Planning Commission. Malawi's Vision - Malawi 2063: An Inclusively Wealthy and Self-reliant Nation. Lilongwe: National Planning Commission; 2020.
62. Oates N, Mwathunga E. A political economy analysis of Malawi's rural water supply sector. Overseas Development Institute; 2018.
63. Resources - RWSN Library - Rural Water Supply Network [Internet]. [cited 2025 Jun 12]. Available from: https://www.rural-water-supply.net/en/resources
64. Braun V, Clarke V. Toward good practice in thematic analysis: avoiding common problems and be(com)ing a knowing researcher. Int J Transgend Health. 2022;24(1):1–6. https://doi.org/10.1080/26895269.2022.2129597 PMID: 36713144
65. Braun V, Clarke V. Using thematic analysis in psychology. Qual Res Psychol. 2006;3(2):77–101. https://doi.org/10.1191/1478088706qp063oa
66. Brown J, Issacs D. The World Café: Shaping Our Futures Through Conversations That Matter. Berrett-Koehler Publishers; 2005.
67. Goldsmith L. Using framework analysis in applied qualitative research. Qual Rep. 2021. https://doi.org/10.46743/2160-3715/2021.5011
68. Chung IM, Sophocleous MA, Mitiku DB, Kim NW. Estimating groundwater recharge in the humid and semi-arid African regions: review. Geosci J. 2016;20(5):731–44. https://doi.org/10.1007/s12303-016-0001-5
69. Hinton RGK. Challenges and solutions towards reaching SDG6 in Malawi. Glasgow: University of Strathclyde; 2024. Available from: https://doi.org/10.48730/gn16-xx04
70. Malawi Government. National research agenda operationalizing the Malawi 2063 first 10-year implementation plan (MIP-1). Lilongwe: National Commission for Science and Technology, National Planning Commission; 2023.
71. Hughes DA. Facing a future water resources management crisis in sub-Saharan Africa. J Hydrol: Region Stud. 2019;23:100600. https://doi.org/10.1016/j.ejrh.2019.100600
72. Government of Malawi. Status of groundwater monitoring network in Malawi. Lilongwe: Groundwater Division, Department of Water Resources and National Water Resources Authority (NWRA), Ministry of Water and Sanitation; 2023.
73. Government of Malawi. Report on assessment of groundwater monitoring wells in Malawi. Lilongwe: Groundwater Division, Departmenr of Water Resources. BASEflow, BAWI Consultants; 2022.
74. Too much and not enough. Nat Sustain. 2021;4(8):659–659. https://doi.org/10.1038/s41893-021-00766-8
75. Kalin RM, Mleta P, Addison MJ, Banda LC, Butao Z, Nkhata M. Hydrogeology and groundwater quality atlas of Malawi. Bulletin. 2022;151.
76. Government of Malawi. Water Resources Act. No. of 2013. 2013.
77. Zuka SP. Contesting institutional engineering for decentralized natural resource governance in Malawi. Sage Open. 2016;6(3). https://doi.org/10.1177/2158244016659527
78. Wahba J, Byrns S, Smith T. Improving water point functionality in Malawi: making the case for minimum financing for direct support. 2017.
79. Phiri E, Rowley PN, Blanchard RE. Addressing challenges in delivering sustainable rural water provision using solar water pumping in Malawi: a stakeholder analysis. Energies. 2023;16(23):7758. https://doi.org/10.3390/en16237758
80. UNICEF Malawi. Malawi Climate Resilient WASH Financing Strategy 2022-2032. Lilongwe: UNICEF Malawi; 2022.
81. Government of Malawi. Waterworks Act. No. 17 of 1995. 1995.
82. Pories L, Fonseca C, Delmon V. Mobilising finance for WASH: getting the foundations right. Water. 2019;11(11):2425. https://doi.org/10.3390/w11112425
83. Tsekleves E, Fonseca Braga M, Abonge C, Santana M, Pickup R, Yongabi Anchang K. Community engagement in water, sanitation and hygiene in sub-Saharan Africa: does it WASH? J Water Sanit Hyg Dev. 2022;12(2):143–56.
84. Chidya RC, Mulwafu WO, Banda SC. Water supply dynamics and quality of alternative water sources in low-income areas of Lilongwe City, Malawi. Phys Chem Earth Parts A/B/C. 2016;93:63–75.
85. Lorenzen G, Sprenger C, Pekdeger A. A simple method to hide data loggers safely in observation wells. Ground Water. 2011;49(3):450–3. https://doi.org/10.1111/j.1745-6584.2010.00771.x PMID: 21087249
86. Tulloch AIT, Possingham HP, Joseph LN, Szabo J, Martin TG. Realising the full potential of citizen science monitoring programs. Biological Conservation. 2013;165:128–38. https://doi.org/10.1016/j.biocon.2013.05.025
87. Theobald EJ, Ettinger AK, Burgess HK, DeBey LB, Schmidt NR, Froehlich HE, et al. Global change and local solutions: tapping the unrealized potential of citizen science for biodiversity research. Biol Conserv. 2015;181:236–44. https://doi.org/10.1016/j.biocon.2014.10.021
88. Bonney R, Cooper CB, Dickinson J, Kelling S, Phillips T, Rosenberg KV, et al. Citizen science: a developing tool for expanding science knowledge and scientific literacy. BioScience. 2009;59(11):977–84. https://doi.org/10.1525/bio.2009.59.11.9

89. Haklay M. Citizen science and volunteered geographic information: overview and typology of participation. Crowdsourcing geographic knowledge. Springer Netherlands; 2013. pp. 105–22. https://doi.org/10.1007/978-94-007-4587-2_7
90. Government of Malawi. Standard operating procedure for groundwater level monitoring. Lilongwe: Ministry of Agriculture, Irrigation and Water Development, Groundwater Division; 2016.
91. Government of Malawi. Standard operating procedure for operation and management of the national groundwater database. Lilongwe: Ministry of Agriculture, Irrigation and Water Development, Groundwater Division; 2016.
92. Government of Malawi. Standard operating procedure for drilling and construction of national monitoring boreholes. Lilongwe: Ministry of Agriculture, Irrigation and Water Development, Groundwater Division; 2016.
93. Government of Malawi. Standard operating procedures for groundwater use permitting [SOP]. Lilongwe: Ministry of Agriculture, Irrigation and Water Development, Groundwater Division; 2016.
94. Adelana SMA, Taylor R, Tindimugaya C, Owor M, Shamsudduha M. Monitoring groundwater resources in Sub-Saharan Africa: issues and challenges. IAHS Red Book Publication. 2009;334:103–13.
95. Barrington DJ, Sindall RC, Chinyama A, Morse T, Sule MN, Beale J. The persistence of failure in water, sanitation and hygiene programming: a qualitative study. BMJ Glob Health. 2025;10(2). https://doi.org/10.1136/bmjgh-2024-016354 PMID: 10.1136/bmjgh-2024-016354
96. Barrington DJ, Sindall RC, Chinyama A, Morse T, Sule MN, Beale J, et al. The persistence of failure in water, sanitation and hygiene programming: a qualitative study. BMJ Glob Health. 2025;10(2):e016354. https://doi.org/10.1136/bmjgh-2024-016354 PMID: 40000060