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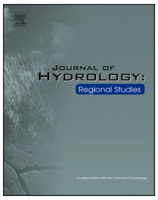

Stakeholder-informed approach improves national modelling of water resources for a Sub-Saharan African basin

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ABSTRACT

Study area: Lake Malawi Shire River Basin (LMSRB), Southern Africa
Study focus: Improving our understanding of groundwater resources is essential for effective management and sustainable development. Here, we apply a global hydrological model, the Community Water Model (CWatM, 5 arc minute resolution) with MODFLOW6 (5 km resolution), to gain understanding of Malawi's understudied groundwater resources. The study applies semi-structured stakeholder interviews to inform simulation of water management in a data scarce context. Model simulation was validated against streamflow data for 35 rivers. 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).
New hydrological insights for the region: Model modifications, including simulation of sanitation usage (specifically pit latrines) and wetland simulation, significantly improved streamflow simulation performance; the unmodified model had 71 % adequate streamflow simulation, increasing to 89 % following stakeholder-informed modifications. Modelling national water resources in other southern African countries should consider similar modifications. Our model shows a consistent decline in groundwater levels since 1980 (the beginning of our study period). We estimate an annual decrease of 0.59 km^3 (approximately 0.1 %) in groundwater storage in Malawi from 1980 to 2009, raising significant concerns about the country's future water security. This model provides unprecedented insight into Malawi's water security, particularly regarding the unseen but critical groundwater resource.

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1. Introduction

Malawi is often regarded as a water-rich country, primarily due to the presence of Africa's third-largest lake, and the fifth-largest globally by volume (Herdendorf, 1984), known as Lake Malawi, Lake Nyasa or Lake Niassa. Despite the prevalence of surface water, groundwater is arguably the country's most essential source of water, supplying 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 and 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), further emphasizing their importance in considering any aspect of Malawi's water resources. Understanding the nature of groundwater is critical for guiding sustainable water policy. Yet, despite this importance, Malawi's groundwater resources remain largely understudied and misunderstood (Kalin et al., 2022).

Management of Malawi's groundwater has been hampered by insufficient groundwater monitoring (Mleta, 2010; International Groundwater Resources Assessment Centre (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 the construction of monitoring wells began in 2009, at least ten are already known to be non-functional due to vandalism (Kalin et al., 2022). When monitoring is conducted, it is not evenly distributed, with some regions having no groundwater monitoring (Mleta, 2010), limiting national-level groundwater assessment. Furthermore, regular monitoring is limited even when infrastructure is available, and data is often not appropriately downloaded and stored (Kalin et al., 2022). Challenges in managing and coordinating groundwater monitoring data have been identified as barriers to monitoring within Malawi and the Southern African Development Community (SADC) (International Groundwater Resources Assessment Centre (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, 2022). Consequently, understanding the current quantity of and historical trends in Malawi's groundwater storage is greatly lacking. The only national estimate of Malawi's water resources applies a water balance method. It places Malawi's total national groundwater storage between 96.7 and 1108 km^3 (not including the saturated thickness of each aquifer unit), presenting an exceptionally large range (Kalin et al., 2022). Some studies point to localized groundwater decline (Sichone, 2024) but there is not national data to estimate or support this. National-level and long-term data are needed to inform decision-making and guide water management. The lack of understanding of quantity and groundwater availability trends limits effective and informed policymaking.

Hydrological modelling can provide a system to fill this knowledge gap. Through simulating water resource dynamics, hydrological modelling can inform the 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 the potential to provide holistic water resource understanding. However, many large-scale models fail to simulate groundwater flow adequately (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). The coarse spatial resolution of large-scale modelling further limits practical modelling efforts by limiting model performance, particularly for groundwater (Guillaumot et al., 2022; Reinecke et al., 2020). These constraints mainly limit the appropriate modelling of water table depth (Guillaumot et al., 2022; Reinecke et al., 2020), which is essential in considering groundwater resources and groundwater dynamics.

Ensuring appropriate representation of human demand for water resources has been another development area 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 and water resources model, including human impacts on water resources and integrating surface and groundwater (Burek et al., 2020). Crucially, through water demand modelling, the model enables the 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 MODFLOW6 (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 an understanding of water resources and inform policy (Bhave et al., 2022, 2020). Whilst valuable, such models have mainly been 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, particularly groundwater-based, water resource understanding. Where detailed groundwater-specific modelling and analysis in Malawi has been conducted, these have been on the catchment level (Sehatzadeh, 2011; Sichone, 2024) and cannot respond to national-level calls for increased groundwater understanding. Applying global hydrological models to develop a sense of national-level water resources can provide a beneficial tool for 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 (Hanasaki et al., 2022) particularly in areas with limited in situ data (Chavarría et al., 2022). Localised models, accounting for locally derived boundary conditions and human activities can greatly enhance regional water resource simulation of global models (Hanasaki et al., 2022), making them a valuable tool in enhancing water resource dynamics. However, the need for improved hydrological modelling in areas of data scarcity alongside the challenge of poor model performance in such contexts presents a paradox: many areas where global hydrological models can be most beneficial to fill knowledge gaps may also show the poorest model performance. Methodologies to enhance local simulation of global hydrological models in data scarce regions are greatly needed.

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; Agrawal et al., 2024). 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; Agrawal et al., 2024). In addition to model performance and co-production benefits, integrating stakeholders into model generation can generate hydrological models with improved credibility and more helpful 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 groundwater flow model MODFLOW6 to an understudied water resource area, exploring how stakeholder-informed co-production can enhance hydrological modelling in a data-scarce region. Considering the context of Malawi's water resources, the study provides essential insights into the challenges faced in the region. It improves our understanding of how global hydrological models can more accurately represent water resources in other Sub-Saharan African basins. We explore the potential of stakeholder-informed modelling to meet the challenge of representing local-level water resource dynamics (Chavarría et al., 2022), providing policy-maker relevant information (Megdal et al., 2017), and generating useful model outputs (Bhave et al., 2020). By comparing the model performance of a 'default' calibrated model for the basin alongside that of a 'stakeholder-informed' calibrated model, the capacity for stakeholder-informed modelling to enhance model performance is evaluated. The development of a basin-wide hydrological model, precisely one that couples groundwater and surface water, then enables the development of the understanding of Malawi's groundwater, directly responding to calls for an enhanced understanding of groundwater resources (Kalin et al., 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?

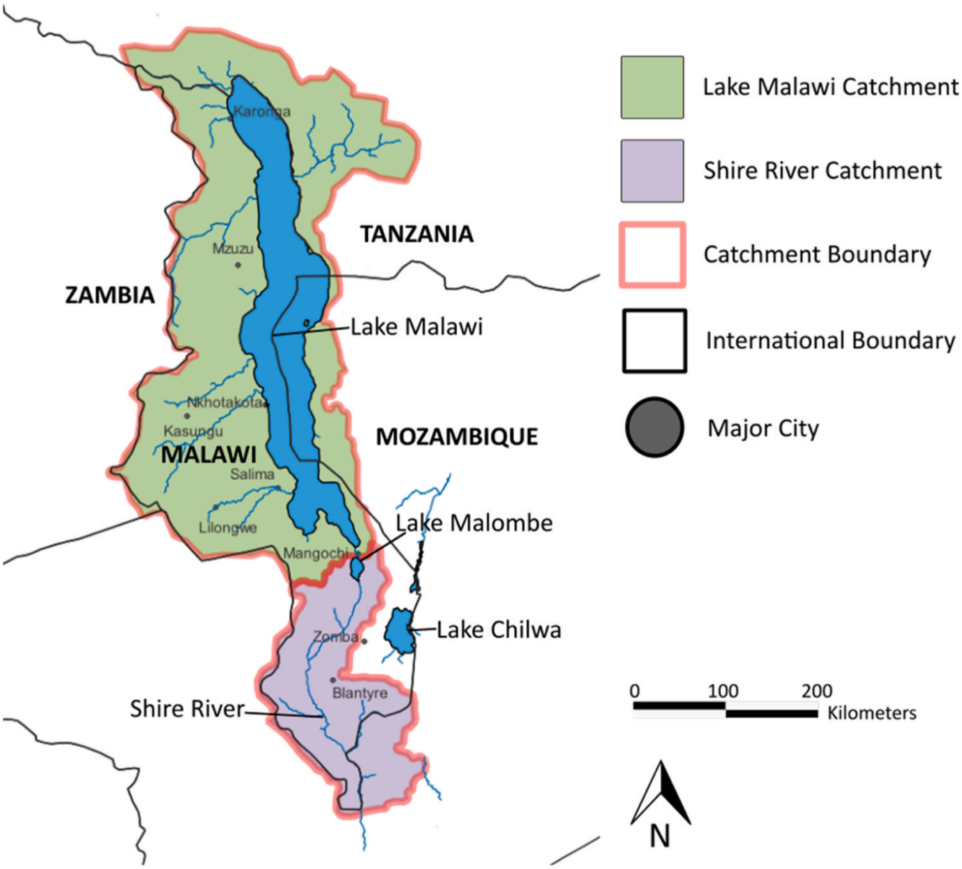

Fig. 1. Study area, the transboundary Lake Malawi Shire River Basin (LMSRB) covering 94 % of Malawi's surface area. The Lake Malawi catchment and Shire River catchment are shown in green and purple respectively. Makor lakes and cities are marked.

2) What is the status of Malawi's groundwater resources, and how has this changed in recent years?

2. Methodology

2.1. Context and study area

This study focuses on the Lake Malawi Shire River Basin (LMSRB), a catchment made of the Lake Malawi Basin and the Shire River basins (Fig. 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 LMSRB is central to Malawi's water security (Nhamo et al., 2016), covering approximately 94 % of Malawi's land area, with the remaining 6 % falling within the Lake Chilwa drainage basin (Kalin et al., 2022b). Whilst the LMSRB lies primarily within Malawi, the LMSRB is a transboundary system with ~21 % of the catchment 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 LMSRB forms part of the East African Rift Valley and has a diverse physiography consisting of highlands, plateau areas, the rift valley escarpment, and the rift valley floor. Most of the country is covered by the plateau region which includes wetland areas 'dambos' that rain into the with the rift valley floor, extending along the shore of Lake Malawi and upper shire valley (Upton et al., 2018).The floor of the rift valley is made up of alluvial deposits with sedimentary rocks running parallel to the shores of Lake Malawi. Malawi's complex hydrogeology has important implications for groundwater flow, most of the basin is dominated by fractured basement aquifers with higher-yielding aquifers in alluvial and lacustrine sediments found largely along Lake Malawi and in the Shire Valley (Kalin et al., 2022).

Water resources are also governed by the climatic patterns, 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). Throughout the dry season (May-October), groundwater is vital in sustaining river flows, making up to 97 % of river flow through baseflow (Kelly et al., 2020). 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 most considerable surface water storage, with a volume of 8400 km^3(Sehatzadeh et al., 2017). 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 the land area being used for agriculture in 2021 (World Bank, 2025). Most 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 is estimated to be subsistence farmers (National Planning Commission (NPC), 2021). Smallholder farmers typically operate rainfed agriculture; however, smallholder irrigation has been significantly increasing (Mapemba et al., 2020); an estimated 41,053 ha of Malawian smallholder land was under irrigation in 2016, rising to 59,655 ha in 2019 (Chafuwa, 2017; Government of Malawi, 2019). The 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 is part of an ongoing process of stakeholder engagement spanning over 20 years, forming part of a partnership between the Scottish and Malawian governments under the Climate Justice Fund Water Futures Program. Ongoing work has developed an understanding of groundwater and surface water resources, notably resulting in a revised Groundwater Atlas, contributing to much of the conceptual understanding of the water dynamics within this paper (Kalin et al., 2022).

Stakeholder consultation was sought to guide the modelling process and to validate the model. Blackwood et al. (2021) identified key stakeholders involved in the Malawi water sector, identifying the critical groups of stakeholders as government, coordination, NGOs, donors, private sector, and education and research (Blackwood et al., 2021). Drawing on such literature (Adams and Zulu, 2015; Blackwood et al., 2021) and prior engagement, this study identified a range of key stakeholders from across the Malawian water sector spectrum to provide expertise on national water management practices. The study then applied snowball sampling to identify stakeholders of interest through stakeholder recommendations further. Twelve stakeholders from eight key governmental and non-governmental organisations were identified and interviewed, providing expert opinions and perspectives on water management in Malawi. The selected organisations are summarised in Supplementary Information Table S1. These organisations were chosen to provide engagement with multiple stakeholders from different aspects of water management in Malawi.

Stakeholder engagement was conducted in two phases. Phase one was used to inform initial model development through semi-structured interviews of expert stakeholders conducted in June and July 2023. The interviews involved asking respondents for feedback on the model structure and how best to represent the Malawian context. During interviews, the overall model structure of CWatM was discussed, and stakeholders were encouraged to comment on the model structure, identifying gaps and areas where the model should be tailored to the context. The focus was placed on the major drivers of groundwater use in Malawi. Phase two validated and refined the stakeholder-informed model through further semi-structured interviews conducted in December 2024 and January 2025. The second phase of interviews also asked for information on major drivers of groundwater use in Malawi. Stakeholders were asked for feedback to verify changes already suggested and made to the model. Interview outlines are summarised in the Supplementary Information 6.1. All interviewees provided informed consent. Following stakeholder interviews, feedback was evaluated and categorised into thematic groups.

2.3. CWatM model initalisation and modification

This research used the open-source 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-informed models were run basin-wide at a high spatial resolution of 5 arcminutes (approximately 10 km at the equator). 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 reservoir release, with different release volumes in the dry and wet seasons, was set based on literature estimates as a proportion of the lake volume (Bhave et al., 2020).

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

A stakeholder-informed model was developed based on stakeholder feedback and knowledge of the hydrological context. Fig. 2 provides an overview of the use of stakeholder feedback in the modelling process of both the 'default' and 'stakeholder-informed' models. Table 1 summarises the areas of modification.

2.4. Model-tuning

Model tuning consisted of validation of climatic inputs (evapotranspiration and precipitation) using remote sensing estimates. Following validation of inputs, soft calibration was performed through comparison of observed and simulated river discharge at nationally representative monitoring stations.

Soft calibration was achieved through a comparison of observed and simulated streamflow. Model parameters were iteratively adjusted to achieve best model overall streamflow simulation for both the default and stakeholder informed models. River flow data was provided by the Government of Malawi, Ministry of Water and Sanitation. Monitoring stations on 35 rivers representing all Malawi regions were selected for comparison, all monitoring stations had more than 15 years of data. Where multiple monitoring stations with sufficient data were available for a given river, the monitoring station furthest downstream was selected. The monitoring stations and rivers are summarised in Appendix Table S2 alongside the dates for which measured streamflow data was available. Ten major rivers were identified as important monitoring stations and are highlighted in bold. The locations of the discharge stations (with major river discharge stations labelled) are shown in Fig. 3.

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

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

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 a moderate model predictive performance of stream flow (Elmi et al., 2024). To evaluate the default model's performance compared to the stakeholder-informed model, KGE values at the 35 national monitoring stations, shown in Fig. 3, were compared, assessing the number of discharge stations in which streamflow was adequately represented.

Basin-wide scale model validation was undertaken by comparing model outputs with remote sensing observations of precipitation and evapotranspiration, the model's major input and output (respectively). 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, 2012; Huffman et al., 1997, 2007, 2001, 1995). Meanwhile, five evapotranspiration remote sensing datasets, at varying temporal and spatial resolutions, were used for comparison: NASA GLDAS (Rodell et al., 2004), MODIS 500 m (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

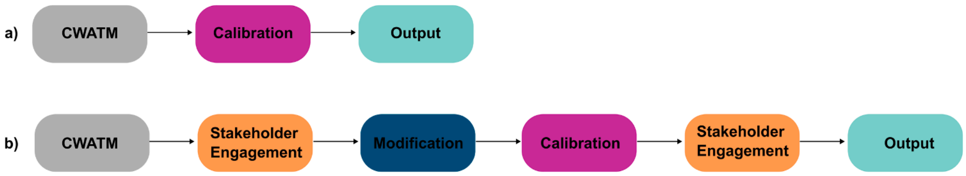

Fig. 2. Incorporation of stakeholder engagement into the modelling structure showing the difference in a) the 'default' model and b) the 'stakeholder-informed' models Stakeholder engagement took the form of semi-structured stakeholder interviews.

Table 1

Areas of modification identified by stakeholders, as well as literature and methodology for modification. Modifications primarily identified from stakeholder engagement are marked with an asterisk (*), whilst modifications primarily from literature are marked with a delta (Δ).

Area of modification	Modification	Method of modification
Hydrological/ geomorphological representation	Groundwater lateral flow *, Δ	The CWatM hydrological model was coupled with the three-dimensional finite-difference groundwater flow model MODFLOW6 at 5 km resolution (Langevin, 2017; Guillaumot et al., 2022).
	Aquifer properties Δ	A shapefile of the three main aquifer units in the study area was generated to capture the properties 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 a 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 Supplementary Information Table S2.
	Wetlands/ Dambos Δ	A wetland shapefile was generated using satellite imagery to identify areas as wetlands to simulate water retention within wetlands. The channel gradient was reduced in wetland areas, 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) *	A raster file for the catchment was developed at a 5 arc minute resolution. Regions within Malawi were categorised as urban or rural (Hinton et al., 2024a). In urban areas, 80 % of water demand was assumed to be met by surface water (reservoirs), and the remaining 20 % was met by groundwater (Chavula, 2012). Within rural areas, 20 % of water demand was met from surface water (reservoirs), and the remaining 80 % was supplied from groundwater (Chavula, 2012).
	Domestic water demand *	A raster file of Malawi's population divided by rural and urban areas (Hinton et al., 2024a) 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 considered to be 152 L/person/day.
	Irrigation *	The percentage of land used for smallholder farming was taken from IFPRI Harvest Choice estimates (Koo and Pardey, 2020). We assume that 5 % of smallholder land is irrigated (to the same intensity as commercially irrigated farmland) (World Food Programme, 2021; Wiyo and Mtethiwa, 2018). It was assumed that irrigation was evenly distributed among all land with smallholder agriculture. To account for the increase in irrigated cropland, land classified as grassland was selected for reclassification to irrigated cropland.
	Sanitation (pit-latrines) *	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).

estimate breaks down evaporation into three components (vegetation transpiration, Ec, interception from vegetation canopy, Ei, and soil evaporation, Es). To evaluate total evaporation, these were summed (Zhang et al., 2019; 2016; Gan et al., 2018).

2.5. Total water storage

Changes in the total water storage (TWS) 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 TWS estimates analysed differences in total water storage compared to the average TWS from 2004 to 2009. Simulated TWS for the basin were compared to the average simulated estimates from 2004 to 2009.

To evaluate the fit of the simulated data to the GRACE data, four goodness of fit indices were employed to better capture the different 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 are summarised in Supplementary Information Equations 1–3,

2.6. Groundwater storage

The model with the best performance was selected based on the number of discharge stations accurately simulated, and the model with the best overall performance for the simulation of GRACE TWS data. The total groundwater storage was evaluated for the model with the 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 to 2009 was analysed to evaluate groundwater storage change over time.

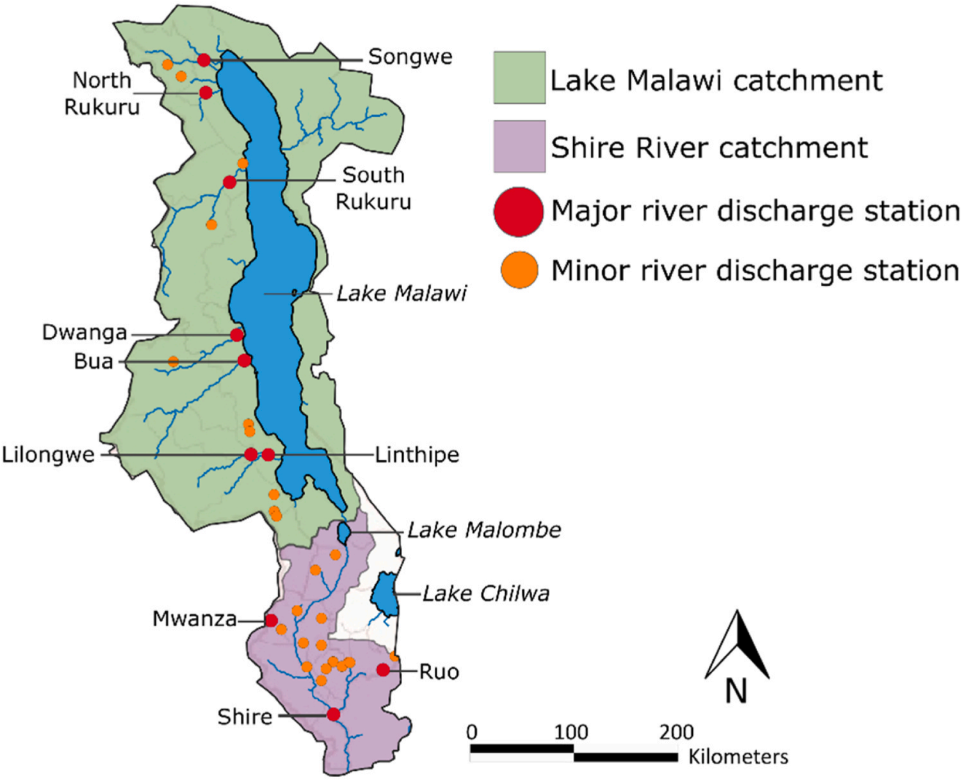

Fig. 3. Locations of discharge stations within the LMSRB used for this study. Discharge stations were investigated for major and minor rivers.

Table 2
Major drivers of groundwater use/ factors to consider in modelling Malawian water resources as identified by stakeholders.

Factors influencing groundwater	Rationale
Domestic water abstraction source (groundwater vs surface water)	The difference in the source of domestic water use in urban and rural areas was mentioned, with urban areas having greater surface water demand. Many urban areas have plans to expand surface water abstraction through further dam construction and piped water developments (Lilongwe Water Board, 2018). Proposals to pipe 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.”
Population growth	Population growth was identified as a major influence on current and future water management. “the key [factor in groundwater demand] is population growth and that largely lack of alternatives – particularly piped water systems in rural areas”
Urban vs rural domestic water demand	The difference in water demand (volume and source) within urban and rural areas was identified as a critical consideration in national water demand dynamics. Urban areas have much higher water demand per capita than rural areas.
Irrigation	Distinction between impacts of commercial agriculture and smallholder agriculture on water resources through the differences in irrigation. Whilst smallholder farmers have less intensive irrigation, it was emphasised that irrigation is practised during the dry season “Almost all smallholder farmers practice some form of irrigation, especially during the dry season.” Current planned developments to increase the extent of commercial agriculture and the generation of ‘megafarms’ are critical considerations for Malawi’s future water demand (National Planning Commission (NPC), 2021). The push to solar-powered pumps for groundwater abstraction will also have significant consequences for groundwater abstraction.
Sanitation (pit-latrines)	The type of sanitation influences both (ground)water abstraction and recharge. Low-quality sanitation was also highlighted as a significant driver of water quality due to faecal water contamination (Hinton et al., 2024b; Graham and Polizzotto, 2013), which was identified as influencing the demand for groundwater/ piped surface water. “We assume that if it’s groundwater and it’s clear then that water is safe”.
Baseflow	The interface between surface water and groundwater via baseflow was emphasised in understanding Malawi’s water resources, “Groundwater is vital to river systems” making coupled surface-groundwater models important to understand the hydrological context.

3. Results

3.1. Stakeholder engagement

Table 2 summarises the main areas identified as influencing groundwater in Malawi from stakeholder interviews. The areas identified included drivers of groundwater use as well as factors influencing recharge and groundwater flow. The areas were identified were used to inform modifications to the CWatM.

The areas of modulation identified by stakeholders and sourced by literature are summarised in Fig. 4.

3.2. Model performance

The major model inputs and outputs were identified as precipitation and evapotranspiration (Supplementary Data, Fig. 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 Figs. 2 and 3.

Streamflow predictive performance was used to evaluate model performance through the Kling-Gutpa Efficiency (KGE). Fig. 5 summarizes the model performance in predicting streamflow for 35 discharge stations nationally. Cases where the streamflow was inadequately predicted (KGE< -0.4) (Elmi et al., 2024) are marked with a triangle. Major rivers are highlighted in bold. Under the default model, 10 of the 35 stations had inadequate model performance (28.6 %), under the stakeholder informed model 4 of the 35 stations had inadequate performance (11.4 %). KGE values are given in Supplementary Information Table S3. 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.

Whilst streamflow simulations for most information stations improved under the stakeholder-informed model, a number of stations

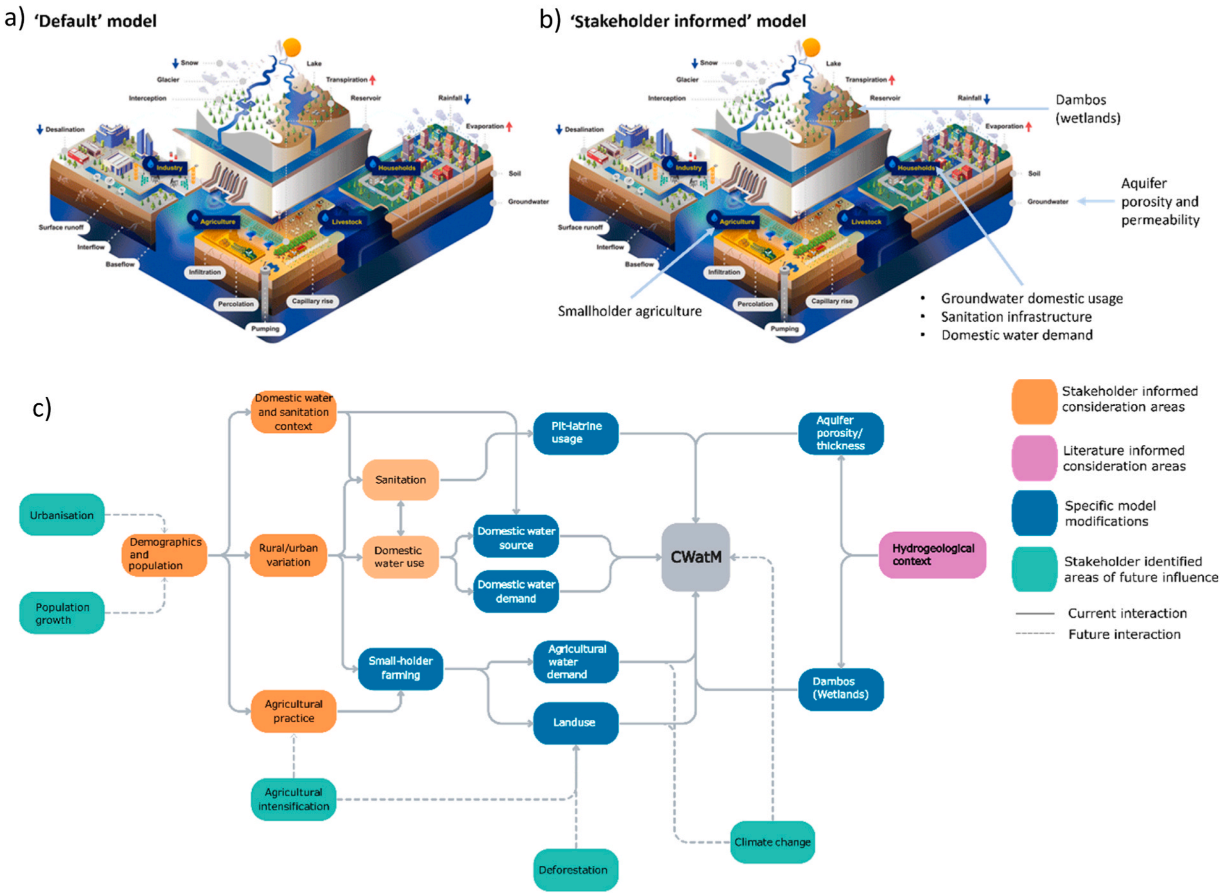

Fig. 4. Areas of modification identified by stakeholders and literature. a) shows the structure of the CWatM model used as the 'default model' here. b) Shows the CWatM model with areas of modification in the 'stakeholder-informed model' as identified by stakeholders and literature. c) Shows the specifc 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).

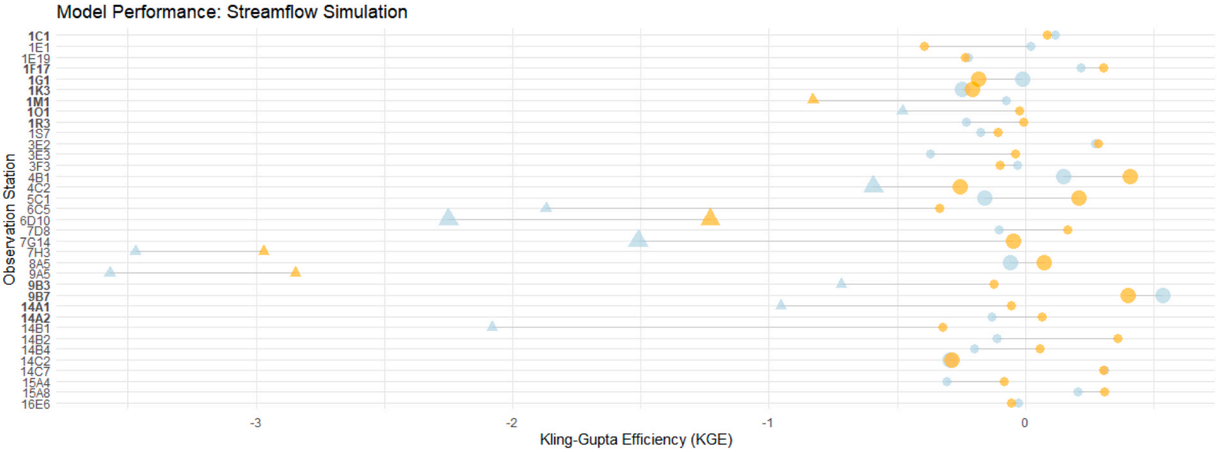

Fig. 5. Model performance of streamflow simulation as measured by Kling-Gupta Efficiency. The default model is marked in blue with the stakeholder-informed model marked in orange. Adequate streamflow simulation is marked with a circle with inadequate simulations represented by a triangle. Discharge stations on major rivers are highlighted in bold and marked by large icons.

showed worse performance or had little performance improvement under the model modifications. Fig. 6 shows the distribution of stations with adequate model performance under the default and stakeholder informed model. The south of the country, particularly the Shire River Basin were areas which showed the greatest improvement in model performance.

3.3. Total water storage

Total water storage was validated against GRACE data, see supplementary information 6.5 The change in TWS compared to GRACE data for the stakeholder-informed model is summarised in, Fig. 7. The figure shows comparison for the stakeholder-informed model as this model had better overall streamflow simulation.

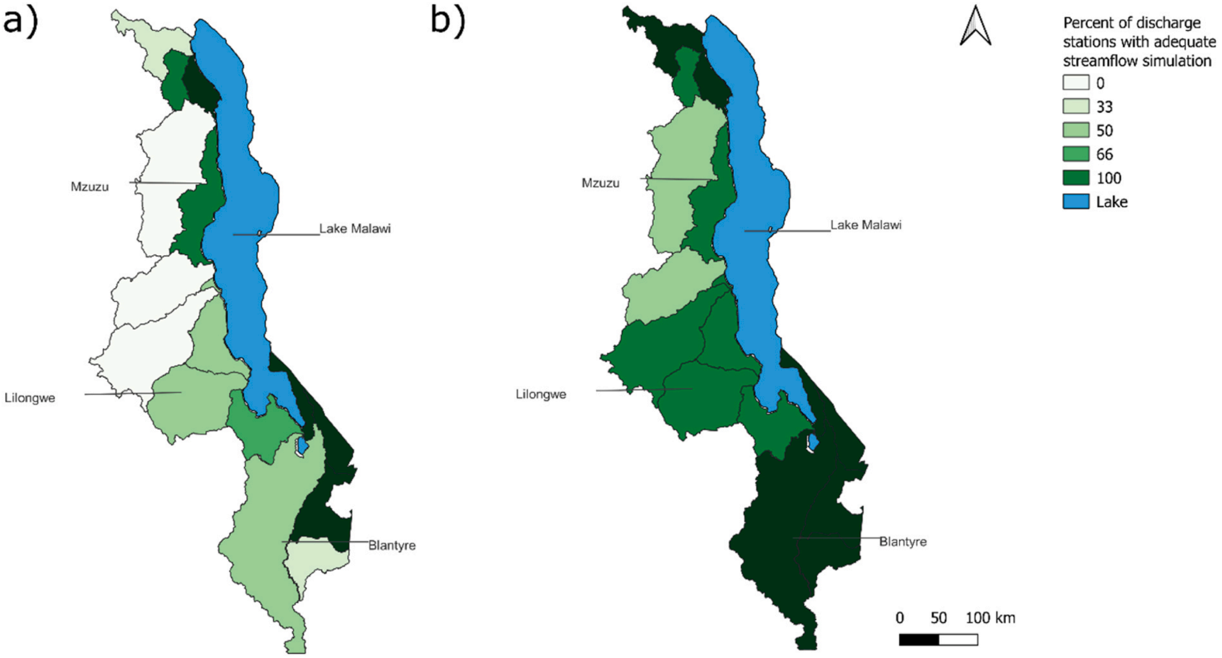

Fig. 6. The percent of discharge stations with adequate streamflow simulation by Water Resource Area (WRA) under a) the default model and b) the stakeholder improved model.

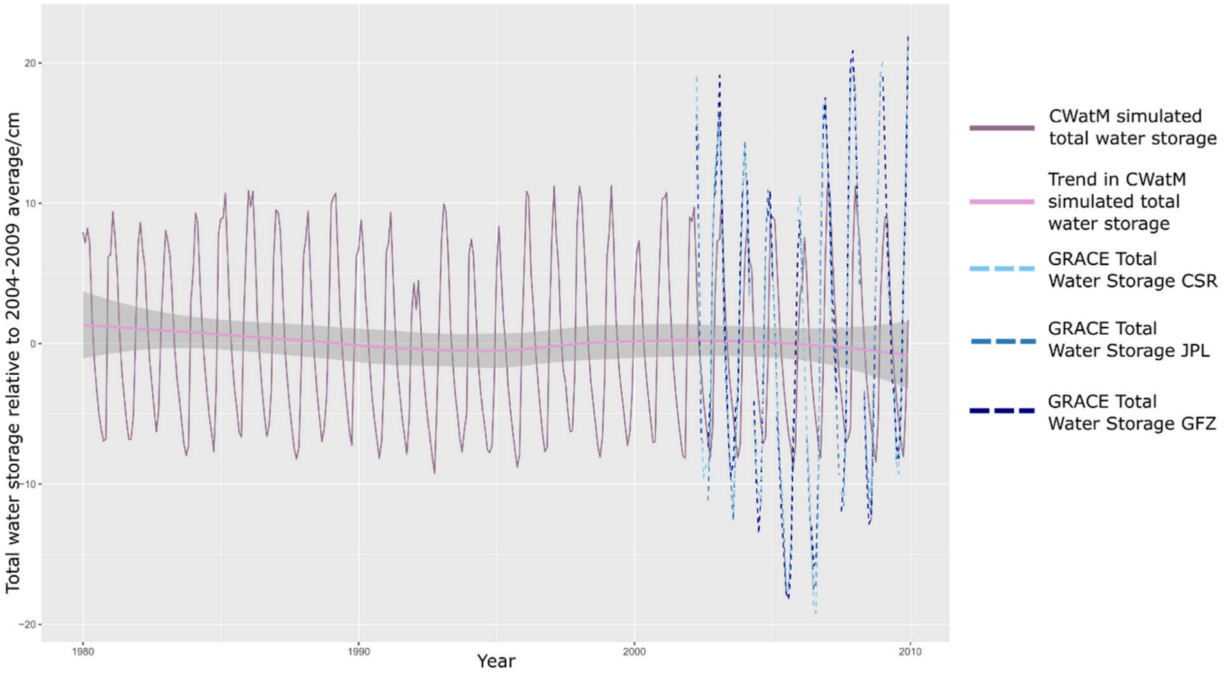

Fig. 7. Total water storage change 1980–2009 (end) within the stakeholder-informed CWatM simulation. Comparison to GRACE data is provided.

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 Fig. 8.

From 1980–2010, there was a decrease in groundwater storage from an average of 670.4 km3 in 1980–652.5 km3 in 2009 (end); this represents a 17.83 km reduction over 30 years and a loss of 2.66 % of initial groundwater storage. This corresponds to an initial equivalent groundwater table depth of 4.27 m in 1980, falling to 4.15 m by 2009, representing an 11.4 cm average drop in groundwater table depth over the 30 years and an average decline of 3.79 mm/ year. A constant linear trend line is fitted (R^2= 0.908)

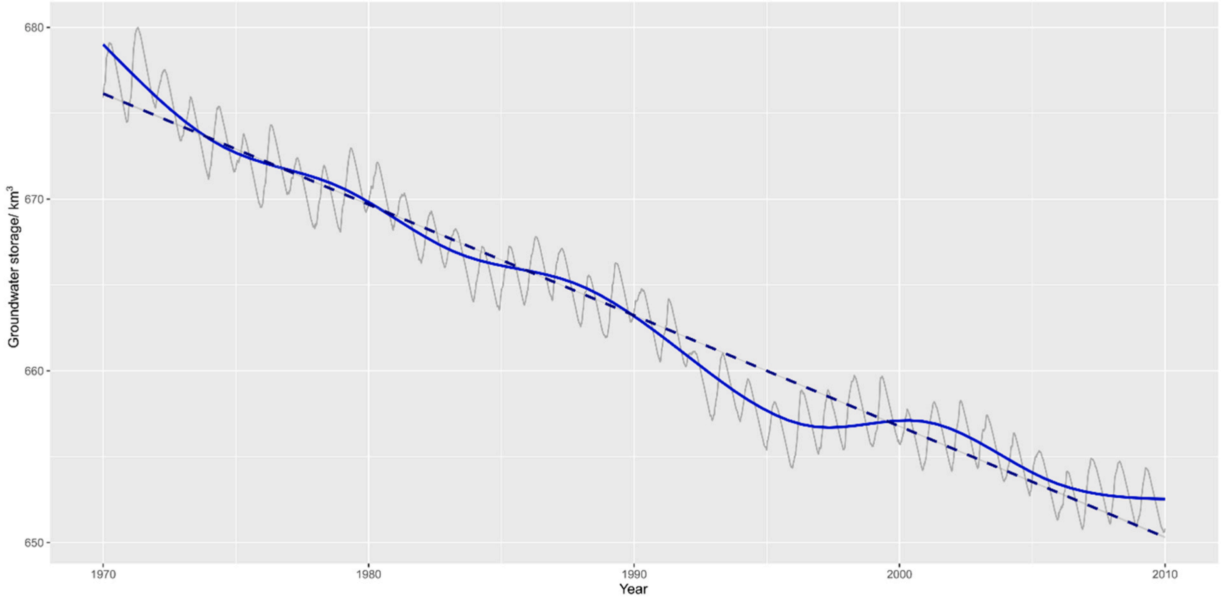

Fig. 8. Change in groundwater storage (km3) from 1980 to 2009 (end). Simulated groundwater storage is shown as grey line. Trends in groundwater storage is shown in blue, loess (solid blue), linear trend (blue dashed).

and 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, requiring significant investment to develop groundwater monitoring wells that require continuous maintenance and, often manual, data collection (Adelana, 2009; Kalin et al., 2022; International Groundwater Resources Assessment Centre (IGRAC), 2013). In regions with 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 where an enhanced understanding of water 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 Polizzotto, 2013), the quantity and trends in Malawi's groundwater storage are largely unknown (Kalin et al., 2022). The lack of understanding of groundwater is mainly due to an inadequate network of monitoring wells, which limits current monitoring, as well as no long-term historical measurements of groundwater data (Kalin et al., 2022). Anecdotal evidence suggests that groundwater levels have been declining, with some areas experiencing a drop of 1 m groundwater/ year (personal correspondence). However, such data is unable to guide national-level policy decisions. Such a lack of understanding of groundwater dramatically restricts the ability of policy decisions to be sufficiently informed and effective in water management (Adelana et al., 2009).

Applying a default version of the global hydrological model, CWatM failed to adequately simulate river flow in 29 % of rivers generally and three out of ten of Malawi's major rivers, limiting inference into the model outputs. Stakeholder engagement was used to enhance the water resource modelling. A stakeholder-informed modelling approach was used to modify the CWatM to better represent Malawi's water context through semi-structured interviews and identifying areas for modulation. 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. Notably, the stakeholder informed model improved streamflow simulation to sufficient performance of two of the three inadequately simulated major rivers, the Lilongwe and South Rukuru Rivers. It is suggested that improvements in simulation of urban water and wetland dynamics respectively were major changes resulting in enhanced modelling of these rivers in particular. The only river not appropriately simulated within the stakeholder informed model is the Dwangwa river within the central region of Malawi, this is discussed further in evaluation of model performance.

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 improved model performance through the enhanced representation of local water resource dynamics. The work highlights that this approach can benefit 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 for modelling Malawi's water resources more effectively and prove consequential for modelling other basins within Sub-Saharan Africa. Some of the modifications of note for modelling similar basins include 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, only one station showed inadequate streamflow simulation in both the default and stakeholder-informed models, station 6D10 on the Dwangwa River. The station is located within Water Resource Area (WRA) 6, featuring many Dambos/ seasonal wetlands (Kalin et al., 2022c). 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 during 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 improved streamflow representation for the two monitoring stations within WRA6, stations 6C5 and 6D10, on the small Mpasadzi and large Dwangwa rivers, respectively. This modification for station 6C5 on the Mpasadzi River resulted in substantial model improvement, from inadequate streamflow prediction (-1.87 KGE) under the default model to adequate prediction (-0.335 KGE) under the stakeholder-informed model. However, after noting the modification, streamflow simulation at station 6D10 on the major Dwangwa River overpredicted streamflow, suggesting the simulated influence of Dambos at this station was too strong. Despite both models having inadequate prediction of streamflow data, the stakeholder-informed model did have improved predictive power (KGE for the major Dwangwa river improved from −2.25 to −1.23 from the default to stakeholder informed model), suggesting that incorporating wetland/ 'Dambo' areas is beneficial for water resource modelling. Further work should build upon the representation of Dambos within this model, particularly concerning 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 assess 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 an 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, neither model fully captured the dynamics of TWS as 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 large lakes, such as Lake Malawi, on TWS estimates from GRACE data (Deggim et al., 2021).

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

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 1108 km^3 (not including the saturated thickness of each aquifer unit) (Kalin et al., 2022). We applied the stakeholder-informed model to investigate Malawi's groundwater resources. The model estimated 653 km 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 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 decrease in groundwater storage of 0.594 km^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 to Malawi's future water availability, likely increasing boreholes facing non-functionality or seasonal water scarcity (Andres et al., 2018). The non-functionality of boreholes is already a pressing issue for Malawi's water security, with 40 % partially non-functional or abandoned (Kalin et al., 2019). Meanwhile, high levels of seasonal water shortage further limit water access, with 34.5 % of boreholes under 10 m 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, 2–5 km^3 annually, with an equivalent change in groundwater table depth annually of 1.3–3.2 cm. The current fluctuations in groundwater storage observed annually, resulting in seasonal water scarcity, are significantly less than the total change in equivalent groundwater table depth observed from 1980 to 2009 of an 11.4 cm average drop in groundwater table depth. Each decade, Malawi has a drop in the average groundwater storage table (3.8 cm) that is more than is witnessed in even the most extreme seasonal fluctuations (3.2 cm); this creates cause for concern considering that such seasonal fluctuations currently result in over a third of boreholes under 10 m experiencing seasonal water shortages. Sustained and continuous depletion of groundwater storage in Malawi may result in many boreholes experiencing seasonal water shortages and more prolonged periods of water shortage. In contrast, boreholes with current year-round access may begin to experience seasonal water availability. Localised estimates of groundwater decline in the Mzimba District, Northern Malawi, using GRACE satellite data estimated annual declines between 0.4 cm and 1.2 cm (Sichone, 2024), showing declines comparable to the estimated national declines here.

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 work being motivated by close stakeholder consultation with partners within Malawi, the model production and calibration for *in situ* data and stakeholder engagement process are explicitly tailored 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 provides 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. 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 developing water resource management plans (Fraser et al., 2020).

The need for 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 did not model groundwater-specific data. Using post-2009 meteorological data would allow comparisons with the limited available groundwater measurements, with the first groundwater monitoring available from 2009 (Kalin et al., 2022). However, it is minimal even when groundwater table data is available, with incomplete data and little sustained monitoring (Kalin et al., 2022; Mleta, 2010). Future work should not only incorporate longer simulations 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, particularly, is expected to influence groundwater resources. Stakeholders emphasized uncertainty in the future of water resources and a call for enhanced modelling of future scenarios of water resources in Malawi. 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 climatic and socio-economic change scenarios. Future model development should also account for changes in government strategy and different policy scenarios, focusing mainly on agricultural development and irrigation policy scenarios, to provide a better framework for future water management scenarios.

The addition of Dambo areas improved model performance. Improved model performance was seen mainly in WRA6 (stations 6C5 and 6D10 on the Mpasadzi and Dwangwa 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 Dwangwa 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 had limited capacity for parameter analysis. Automated calibration was not conducted due to the incorporation of MODFLOW6 (Langevin et al., 2017), as the MODFLOW6 model cannot run under specific conditions and, therefore, crashes under some parameter combinations. Further modelling efforts should enable model function even under unsuitable MODFLOW6 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, has 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 the decline of groundwater; 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, an 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 (International Groundwater Resources Assessment Centre (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 Polizzotto et al., 2013). Not only does groundwater depletion threaten domestic water security, but a growing burden of borehole non-functionality presents a risk of stranded assets and a significant loss of investment in water infrastructure (Kalin et al., 2019). Engaging communities in local-level sustainable water management will safeguard 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 the performance of a global hydrological model for Malawi under default conditions with a stakeholder-informed modified model revealed enhanced performance in areas where stakeholder input was utilized. This adds weight to the influence of stakeholder engagement, resulting in better implementation of recommendations (Basco-Carrera et al., 2021) and improved model performance. Appropriate representation of water demand, including spatial variation in domestic water use, sanitation, and small-holder farming, is essential for better enabling hydrological modelling, particularly for Sub-Saharan African basins.

By developing 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 to 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 increasing population. As emphasized 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*".

Ethics

Informed consent was obtained from all subjects involved in the study. All data collected were in line with, and overseen by, the ethical protocol of IIASA and was agreed with each participant.

CRediT authorship contribution statement

Mads Troldborg: Writing – review & editing, Supervision, Project administration, Conceptualization. **Robert Kalin:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Limbikani Banda:** Writing – review & editing, Investigation, Data curation, Conceptualization. **Macleod Christopher:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Brighton Chunga:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Mikhail Smilovic:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Willaarts Barbara:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Rebekah Hinton:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Dor Fridman:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2025.102574.

Data availability

Data will be made available on request.

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