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A multicriteria analysis of groundwater development pathways in three river basins in Sub-Saharan Africa

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ABSTRACT

Reliance on groundwater in Sub-Saharan Africa is growing and expected to rise as surface water resource variability increases under climate change. Major questions remain about how groundwater will be used, and who informs these decisions. We represent different visions of groundwater use by 'pathways': politically and environmentally embedded socio-technological regimes for governing and managing groundwater systems. We presented policy actors (9 sets), development and research stakeholders (4 sets), and water users (6 sets) in three river basins in Ethiopia, Niger and Tanzania with information on the social and environmental impacts of six 'Groundwater Development Pathways', before gathering their opinions on each, through Multicriteria Mapping (MCM). Participants preferred pathways of low-intensity use, incorporating multiple agricultural, pastoral and domestic purposes, to high-intensity single-use pathways. Water availability and environmental sustainability, including water quality, were central concerns. Participants recognised that all groundwater uses potentially impinge upon one another affecting both the quantity and quality of abstracted water. Across participant groups there was ambiguity about what the most important water use was; each expressed demands for more detailed, certain modelling data. Water users preferred community or municipal-scale management regimes, perceiving that water quality was more likely to be safeguarded by institutions at these levels, whereas policy and development actors preferred individual-scale management, viewed as more efficient in terms of operation and maintenance. We conclude that MCM, combined with more detailed modelling, can provide an effective framework for policy actors to understand other stakeholders' perspectives on groundwater development futures, enabling equitable, inclusive decision-making and governance.

1. Introduction

As climate change amplifies existing high variability in surface water resources in sub-Saharan Africa, groundwater use is expected to rise as communities seek to meet growing freshwater demand and enhance climate change resilience (Taylor et al., 2013; Cuthbert et al., 2019; Cobbing and Hiller, 2019). Considerable dependence upon groundwater exists for domestic water supplies in rural and urban Africa (Foster et al., 2018; Gaye and Tindimugaya, 2019) yet, in 2000, groundwater withdrawals in Africa were estimated to have comprised just 2 % of the groundwater abstracted globally (Fig. 1), due primarily to the low proportion of arable land irrigated (Villholth, 2013). Competing demands anticipated for groundwater, alongside limited monitoring and understanding of groundwater resources, complicate groundwater governance (Hussein, 2018), especially when users and managers do not know how particular activities may impact other users or the

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environment.

The 'Pathways Approach' (Leach et al., 2007) can be used to understand the potential implications of human activities on socio-hydrological systems (Sivapalan et al., 2014). It understands 'pathways' as socio-technical regimes for governing and managing complex systems, such as the hydrological system. These pathways include activities (e.g. crop irrigation), which are embedded in specific environmental and political contexts, and pursue given trajectories into the future. The way they are framed and understood by different stakeholders is an integral part of what they are and how they are managed (Leach et al., 2010a). The Pathways Approach and similar frameworks have been used to study socio-environmental issues including mining (Lu and Lora-Wainwright 2014), epidemics (Leach et al., 2010b), climate change (Colloff et al., 2021) and agri-food systems (Hubeau et al., 2017). Pathways approaches are increasingly used in water management and adaptation science more broadly to 'open up' the range of options under consideration (Wise et al., 2014) while explicitly considering uncertainty (Haasnoot et al., 2013).

There are multiple possible groundwater use and governance pathways in Africa, but we lack information about their implications, and understanding of how decisions can be made about groundwater development, management and governance. To address these knowledge gaps, we worked in three African river basins experiencing growing demand for freshwater for agriculture, industry and household use, as well as uncertainty about how this demand will be met and the resilience of development pathways to climate change. We devised six theoretical African 'Groundwater Development Pathways', each rooted in field data. We presented information to stakeholders in the study basins on the modelled impacts of different activities on groundwater, before gathering their opinions on those activities and impacts using the Multicriteria Mapping (MCM) method (Ross and Stirling, 2004).

Through this, we aim to:

- understand priorities and preferences of different stakeholder groups regarding pathways of groundwater development;
- identify how the positions of different stakeholder groups converged and diverged, and on what grounds;

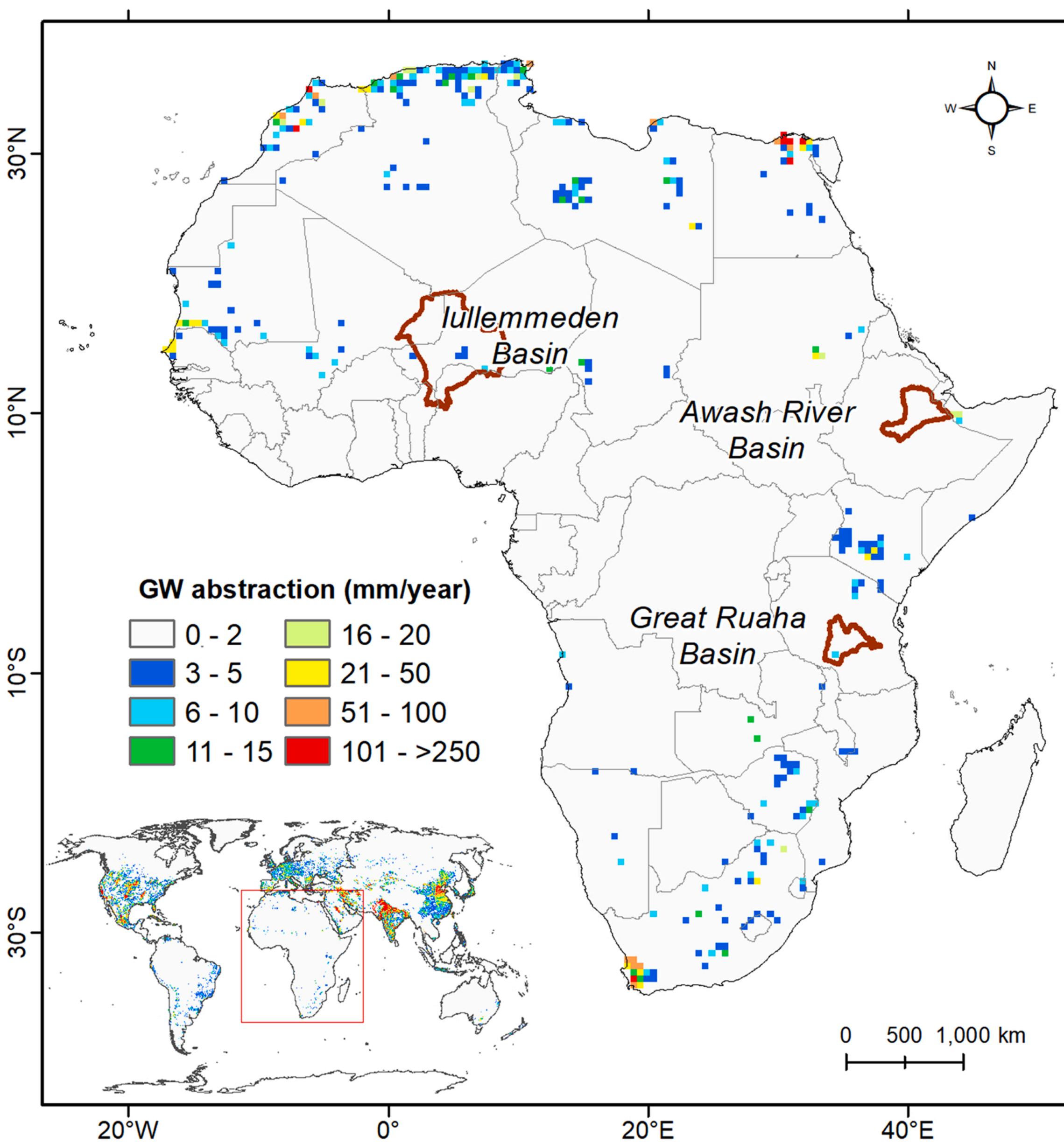

Fig. 1. Gridded estimates of annual groundwater abstraction rates in Africa (Wada et al., 2010, 2012), showing the location of observatories in three river basins.

- report considerations for groundwater management and governance; and
- suggest the role of MCM in groundwater research and decision-making.

1.1. Conceptual considerations

Working with the Pathways Approach highlights considerations of subjectivity, uncertainty, contingency and equity.

Firstly, the Pathways Approach entails a normative assumption that 'sustainable' livelihoods and resource use are desirable, and simultaneously recognises that sustainability may be achieved through any or several 'pathways'. Furthermore, resource users, researchers and policy actors have divergent opinions on what sustainability itself is, as well as how to achieve and maintain it. Thus, achieving sustainability involves understanding what informs these inherently subjective constructions.

Secondly, the Pathways Approach incorporates explicit recognition of uncertainty. In complex systems such as groundwater systems, risk, ambiguity and true uncertainty are common, and sometimes compounded by ignorance (Stirling, 2010).[1] Groundwater levels, well yields, and recharge rates may be unknown (MacDonald et al., 2012; Gaye and Tindimugaya, 2019), let alone how abstraction will influence them or how this will be transferred across space and affect different groups. Groundwater management and governance can consider results of research addressing each of these questions but also needs to recognise the dissent implied by different subjective definitions of sustainability. These variable perceptions emanate from differential interpretations of the viability of the resource and the perceived credibility, legitimacy and saliency of scientific evidence available to inform decision making (Cash et al., 2003; Gleeson et al., 2020).

Thirdly, feedbacks influence the functioning of complex groundwater systems which are inherently political, economic, technological and social, making them contingent. Economic, technological and political drivers influence volumes abstracted from aquifers, but people's socially conditioned demand for water influences whether water scarcity becomes stress (Kummu et al., 2016). Links between groundwater and surface water are also a central and sometimes overlooked consideration, such as when aquifer depletion affects wetlands.

Application of the fourth point, equity, is fraught. The ideal of equitable access to and distribution of water between different water users and functions is often impossible in situations of scarcity. Mehta et al. (2007) consider distinctions between reproductive and productive water uses artificial in the context of multifunctional livelihoods. For example, smallholders may irrigate their own crops using shallow wells, but simultaneously provide labour for commercial agricultural enterprises using deep boreholes, which deplete aquifers to the extent that smallholders' domestic activities become unviable. Uncertainty over groundwater dynamics and priorities of water user groups make it hard to predict where such conflicts may happen. In such situations, Mehta et al. (2007) advocate governance approaches that allow different pathways to co-exist. From a normative standpoint, however, a key consideration is ensuring poor, marginalised and vulnerable water users are not excluded from securing access to and control over a fair portion of the available resource.

The Pathways Approach therefore implies taking a constructivist approach[2] to the identification of groundwater solutions, recognising multiple experiences, opinions, contingencies, uncertainty and the difficulty of achieving equity. Despite acknowledging subjectivities, it is important to simultaneously incorporate positivist objectivity[3] (West et al., 2014), as the material reality of a given situated aquifer is critical to understanding the sustainability of abstraction from it (Beland Lindahl et al., 2016).

In addressing questions of natural resource governance, the scales of management and decision-making must be considered (Biermann et al., 2010). In an attempt to recognise the importance of material resource flows, the dominant Integrated Water Resources Management (IWRM) paradigm defines the basin, rather than the political or administrative division, as the most relevant locus for water management. Thus, we focused our attention on analysing Groundwater Development Pathways from the perspective of basin stakeholders. Nevertheless, we recognise that: "while many practical water management functions are best undertaken at a basin scale, the centrality of the basin envisaged in IWRM since the 1990 s is increasingly questioned. Other scales matter, particularly from the perspectives of water users" (Woodhouse and Muller, 2017: 228).

The next section describes our study contexts. Throughout, we use the terms 'groundwater system' and 'water system' interchangeably, recognising that groundwater is connected to surface water.

2. Study contexts

Our three study observatories are located within the Great Ruaha Sub-Catchment of Tanzania, the Iullemmeden Basin of Niger, and the Awash Basin of Ethiopia. We involved three countries to gain general insights that could be applicable across contexts.

The Great Ruaha Observatory is in the upper reaches of the Rufiji River Basin, southwestern Tanzania (Fig. 2). The study area lies at the base of an escarpment and is underlain by a thick sequence of unconsolidated sands and clays. Here, rivers draining the upland environment converge to form the Usangu Plains that includes the Ihefu Swamp with a single downstream outlet (Kashaigili, 2008; Kashaigili et al., 2009). Shallow groundwater is found within alluvial fans and lacustrine deposits of the Usangu Plains (SMUWC, 2001); interactions between groundwater and surface waters remain unclear. The region sits within the Southern Agricultural Growth Corridor of Tanzania (SAGCOT), where use of groundwater for irrigation is encouraged but currently limited (Mosha et al., 2022). Recent declines in dry-season surface flows have been attributed to overuse of surface water for irrigation though the role of both land-cover (Kashaigili et al., 2006a, 2006b) and climate change (Kihwele et al., 2018; England, 2019) have yet to be fully assessed. Groundwater has hitherto largely been used for domestic purposes. Groundwater use and governance are not major focuses of the National Water Policy of 2002 (Tanzanian MWLD, 2002) and Water Resource Management Act No 11 of 2009 (United Republic of Tanzania, 2009). Groundwater governance is the purview of nine river basin authorities, including the Rufiji Basin Water Office. Other key stakeholders include the Ministry of Agriculture, Livestock Development and Fisheries, as well as various levels of local government and water specific bodies, including registered water user associations.

The Iullemmeden Observatory, within the Niger River Basin,

[1] Risk – Possible outcomes, the probability of their existing, and their effects are known.Ambiguity – It is unknown which outcomes are probable, but should it be, there would be some idea about their effects.True uncertainty – It is known which outcomes are probable, but not how likely each is or their effects. Ignorance - Neither outcomes, the probability of them happening, or their effects are known.

[2] The idea that meanings and understandings can be constructed by actors, based on their experience, and these constructions are valid interpretations of reality. In the context of this work, this relates to aspects such as the importance attached to various groundwater uses.

[3] An approach that recognises there are some immutable truths and realities which are not constructed through human experience. In the context of this work, this largely relates to hydrological aspects such as groundwater levels.

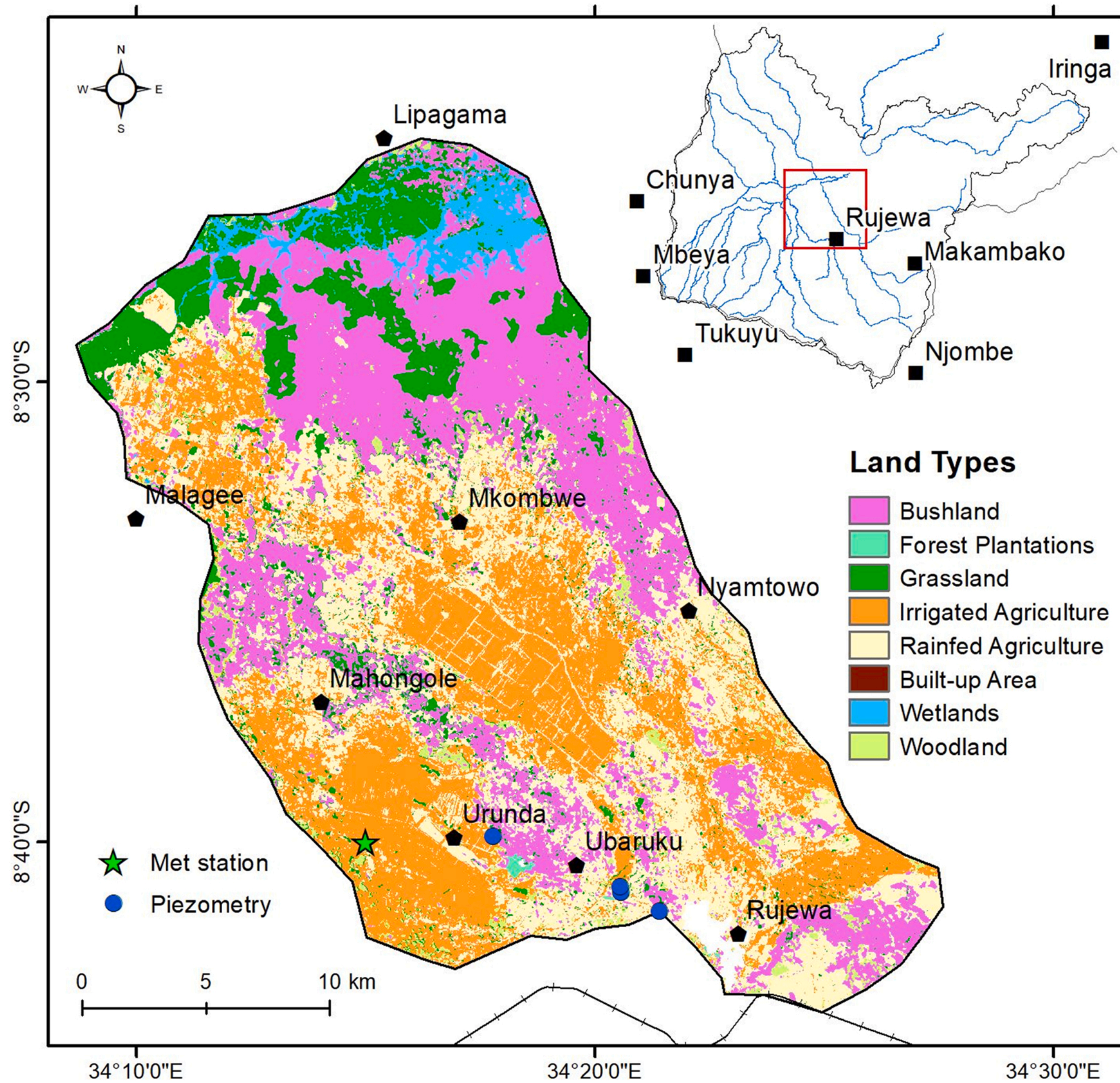

Fig. 2. Map of land cover of the Upper Great Ruaha observatory of south-central Tanzania (Chandrasekharan et al., 2021); the position of this sub-catchment area (636 km^2) is indicated in the inset drainage map, headwaters of the Rufiji Basin.

traverses northwestern Nigeria and southeastern Niger (Fig. 3). River channels are underlain by shallow exploited alluvial aquifers (Issoufou et al., in preparation) that are, in turn, underlain by a regional sandstone aquifer, the Continental Hamadien (Dikouma, 1990; Toyin et al., 2016). Groundwater levels in the Continental Hamadien (CH) have risen regionally in recent decades, even during the Sahelian drought (Sahelian Paradox), due to the conversion of perennial grassland to shallow-root crops (Favreau et al., 2009). Livestock husbandry is culturally and economically important, and a priority groundwater use in the arid north, as recognised by the 1993 Rural Code (Nigerien SPCR, 2018) and the 2016–2030 Sectoral Programme on Water, Hygiene and Sanitation (Nigerien MHA, 2017b). In the study region, competition for water between transhumant herders and irrigators is prominent, especially considering policies aiming to increase irrigated land area such as the 2015 Small Irrigation Strategy of Niger (Nigerien SPSPIN, 2020) and 2012's 'Nigeriens feed Nigeriens' (Nigerien HC3N, 2012). These programmes work alongside the 2017 National Action Plan for Integrated Water Resources Management (Nigerien MHA, 2017a). The transboundary Niger Basin Authority plays a governance role, alongside national water, livestock and agriculture ministries and non-governmental organisations such as the Nigerien National Network of Chambers of Agriculture.

The Upper Awash Observatory is in the headwater catchment of the Awash Basin draining south-central Ethiopia, upstream of the Koka Dam (Fig. 4). Engaged communities reside in an upland area that features the Becho Plains depression. A shallow aquifer of unconsolidated alluvial sands and clays is underlain by the Upper Basaltic Aquifer (WWDSE, 2009). Groundwater monitoring is limited in the basin but there is evidence of competitive abstraction among low-intensity use of shallow groundwater in alluvial sands (e.g. Koka Plain) and commercial floriculture intensively using deep groundwater from the Upper Basaltic Aquifer. Surface water is also used for irrigation. Groundwater is used by industry and households in several urban centres including the national capital, Addis Ababa. The overarching Agricultural Development-Led Industrialisation policy framework and the 2015–2020 Growth and Transformation Plan II (Ethiopian NPC, 2016) are complemented by the 1999 Ethiopian Water Resources Management Policy (Ethiopian MWR, 1999), and Ethiopia's Rural Development Policy (Ethiopian MFED, 2003). Although there is an Upper Awash Basin authority, the basin crosses the boundaries of three states, the administrative authorities of which are also involved in water management, down to the lowest levels of the woreda, and local level water-user organisations.

IWRM is the dominant water policy paradigm in the study contexts, as across much of Africa (Mukhtarov and Cherp, 2014). It considers

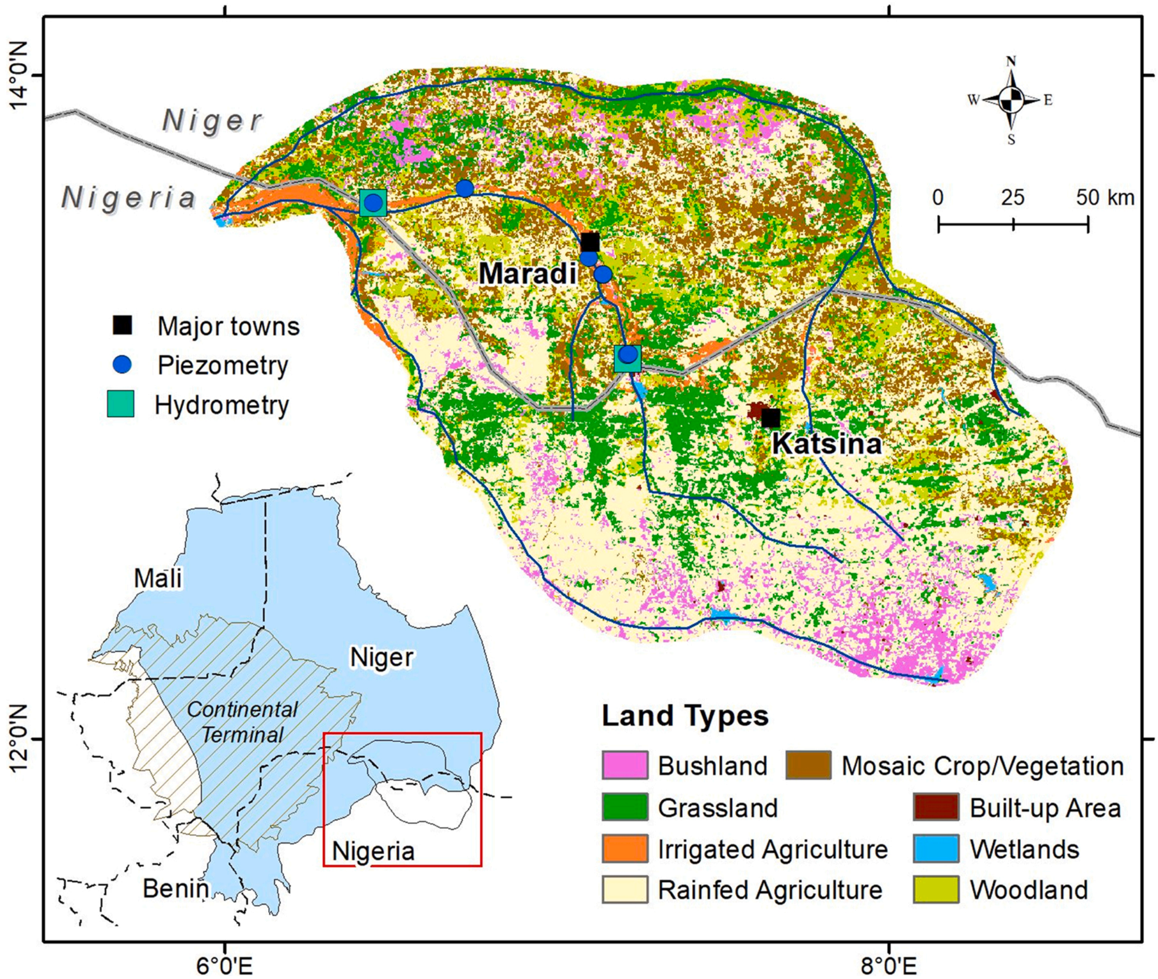

Fig. 3. Map of land cover in the Iullemmeden observatory of southeastern Niger (Chandrasekharan et al., 2021); the position of this sub-catchment area (35, 793 km^2) within the Iullemmeden Basin is indicated in the inset drainage map.

ground and surface water use across multiple spatial and temporal scales, water users and functions, emphasising (sometimes conflicting) principles of equity, (economic) efficiency, and ecological integrity (Savenije and Van der Zaag, 2008). IWRM requires water users' participation in decision making and has thus been linked to Community Based Water Resources Management (CBWRM), in which communities take or share responsibility for local water resource management, often through water user associations. However, in some academic circles IWRM has been criticised as politically naive (Giordano and Shah, 2014; van Koppen et al., 2007; Allouche, 2016), and CBWRM as disingenuously cheap water management (Whaley and Cleaver, 2017). It is acknowledged that IWRM is challenging to implement well. This explains, in part, a more recent strengthened focus on groundwater governance alongside management (Villholth et al., 2012).

3. Methods

The MCM analysis this paper focuses on was preceded by construction of six stylised Groundwater Development Pathways.

3.1. Defining groundwater development pathways

The pathways needed to be general enough to be broadly applicable across contexts, facilitating comparative, multi-site analysis, whilst retaining relevance to local situations. To achieve this, we drew on literature on continental and national policy directions and trends and held workshops with basin level policy actors to understand local strategies for groundwater use. Qualitative interviews and focus groups elicited how local people used groundwater, their local knowledge of groundwater dynamics, and their aspirations.

Thus, the international research team defined six broad, general pathways, versions of which could be applied to each of the study contexts. Every pathway was not necessarily operational in each location, but there was evidence it was at least considered a viable policy option or there were aspirations towards it (e.g., Favreau et al., 2012; Birhanu et al., 2021). Research teams in each basin defined the more precise ways pathways may manifest in each location. The six pathways are described in Table 1.

The term 'scale' in this table refers to level of management and the type of infrastructure, as well as capacity of abstraction facilities. In small-scale pathways, individual households, groups of households or businesses largely manage their own water point. At medium-scale, management is typically the responsibility of communities, municipalities or medium-sized enterprises. International or national corporate entities manage water points in the large-scale pathway. Although multiple functional combinations could theoretically have been represented, these agriculture, livestock and 'multi-use' pathways most closely matched current and future preferred groundwater use trends in the study contexts.

The pathways are stylised descriptions analysts can use to categorize ways of using water across contexts. The objective of arriving at them is not to obtain precise quantitative definitions of how each manifests in a given context, or to support site-specific decision making, but rather to open up conversations about the relative merits and drawbacks of these

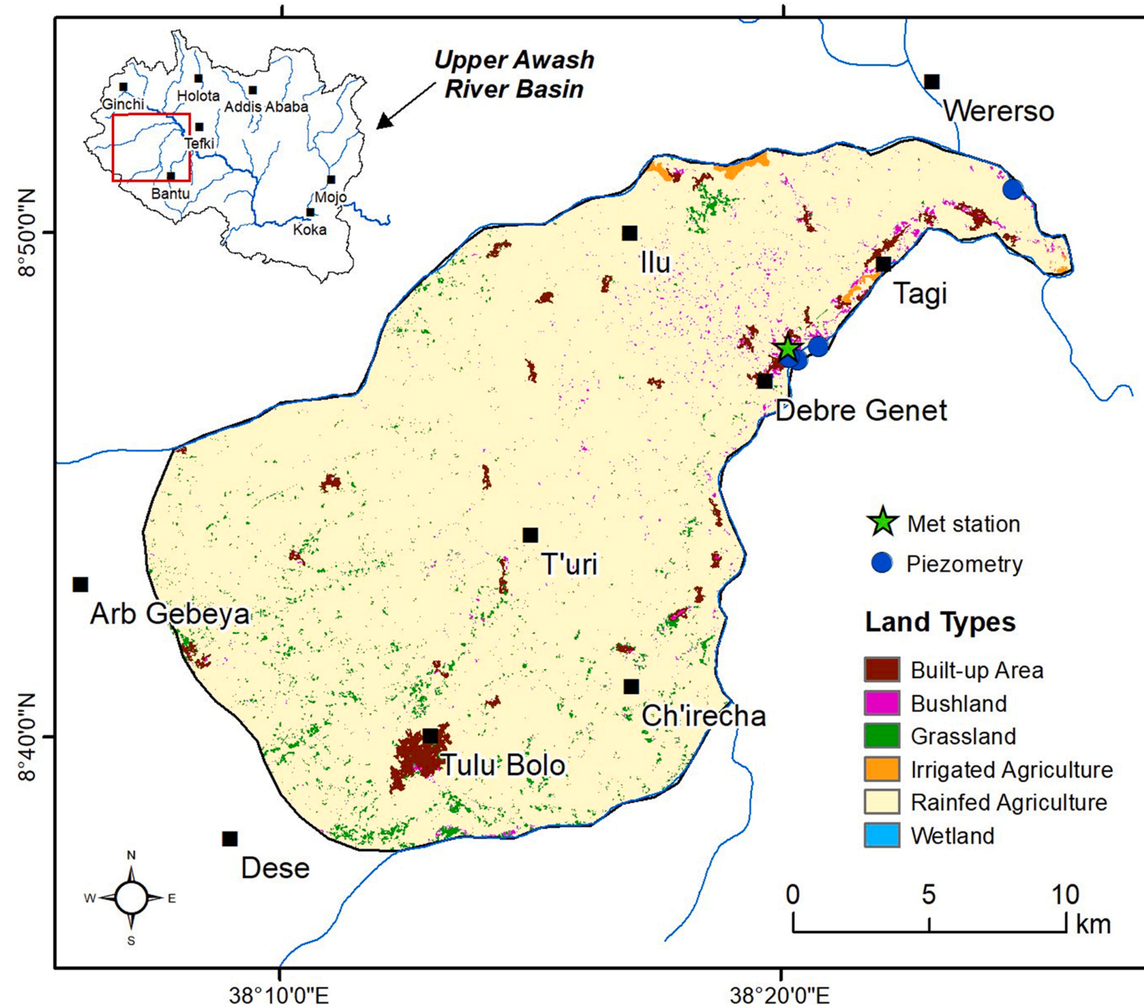

Fig. 4. Map of land cover of the Upper Awash observatory of south-central Ethiopia (Chandrasekharan et al., 2021); the position of this sub-catchment area (446 km^2) is indicated in the inset drainage map, headwaters of the River Awash Basin.

hypothetical scenarios for different groups. We acknowledge that these individual pathways would rarely happen in isolation. For example, deep abstraction by commercial farms may happen simultaneously with household abstraction from shallow wells. Yet, for the purpose of this research, we present each as a stylised scenario, to establish the method of understanding multiple opinions about each. The discussion explains how future research can build upon this to establish multi-pathway models.

Despite their breadth, for modelling purposes in this initial study, it was necessary to choose one pumping scenario to represent each pathway, as indicated in Table 1. We based this on a spatial organisation of abstraction points and an abstraction volume that represented ways of using groundwater indicated in our qualitative interviews and policy review. We referred to hydrological models of the study areas (e.g. Kashaigili et al., 2006a, 2006b; Chan et al., 2020), and studies which had conducted pumping tests in and around our study areas (e.g. Villholth et al., 2012, Maurice et al., 2010, 2019), adding their observations of well depths to our own.

Though these pathways are not endpoints, but ways of using groundwater that entail an explicit temporal dimension, the material implications of each abstraction scenario can be considered an interim 'result'. Section 3.2 describes how we used groundwater modelling to focus on this 'result' five years into the future.

3.2. Groundwater modelling

As pathways were broad, with multiple variations, groundwater model outputs provided participants with a comparative guide to the impacts of various pumping scenarios. Thus, modelling was used to support understanding of participants' decision-making processes and criteria.

Numerical groundwater flow models were constructed using the FREEWAT (FREE and open-source software tools for WATer resource management) platform (Rossetto et al., 2018) within the QGIS geospatial software environment (Anon, 2018) applying MODFLOW codes (Harbaugh, 2005). Groundwater models representing the hydrogeological conditions and dynamics observed within each basin observatory were constructed (see Supplementary Material 1–3 for details) to understand how the magnitude of abstraction modelled in each stylised development pathway would affect water levels in the study areas. Considering current practices of groundwater abstraction in the basins, a single-layered model was used to represent the shallow alluvial aquifer in the Great Ruaha Basin of Tanzania whereas a multi-layered model representing shallow (alluvial) and deep (basaltic) aquifers was employed in the Upper Awash Basin of Ethiopia. For the Iullemmeden Basin of Niger, the single-layer model representing the exploited alluvial aquifer, developed for Tanzania, was employed to provide indicative consequences of abstraction, as uncertainty in the characteristics of this aquifer persisted at the time of running the MCM analysis. Each model was run in transient mode to simulate dry and wet seasons over a

Table 1
The Groundwater Development Pathways.

Pathway name	Brief description
Large-scale agriculture	Farm businesses use groundwater to irrigate marketed crops on farms of 50–100 ha, using a privately owned central pumping system capable of abstracting 25–50 m^3/hour, and distribution technologies such as canals or pipes. These farms and abstraction points are likely to be owned by a small, wealthy powerful elite population, each of whom may operate multiple points.
Medium-scale agriculture	Farmers use groundwater to irrigate marketed crops on farms of 50–100 ha, using a privately or collectively owned central pumping system capable of abstracting 10–20 m^3/hour, and distribution technologies. These farms and abstraction points are likely to be owned by a fairly small, fairly wealthy population segment.
Medium-scale livestock	Ranching businesses use groundwater to water animals in an intensive system, using a privately or collectively owned central pumping system capable of abstracting 10–20 m^3/hour and possibly storage and distribution technologies. These farms and abstraction points are likely to be owned by a fairly small, fairly wealthy population segment.
Medium-scale multi-use	Local people use up to a few hundred litres of groundwater a day per household, for domestic purposes, small-scale gardening and husbandry of a few animals. Water is obtained from a central water point with a pumping system capable of abstracting 10–20 m^3/hour, managed by a central municipal or collective body. Water is piped or carried to individual households depending on amounts used.
Small-scale agriculture	Farmers use up to a few thousand litres of groundwater a day irrigating subsistence and marketed crops on farm of under 5 ha. Water is abstracted from shallow, generally hand dug, privately owned wells, with capacities of 5–10 m^3/hour. Almost all farmers would have access. Some intermediate technologies such as motor pumps and polytanks are used, and these are usually financed by individuals in a farmer-led approach. In study sites, these are located close to settlements.
Small-scale multi-use	Local people use a few hundred litres of groundwater a day per household, for domestic purposes, small-scale gardening and husbandry of a few animals. A few hundred litres of water a day is abstracted by hand or sometimes motor pump from privately owned shallow, generally hand dug wells with capacity of 0.5–5 m^3/hour. All people would have access.

five-year period. Spatially distributed, stylised abstraction points with pumping capacities indicated in Table 1 were applied over the model domain to simulate groundwater levels at the end of the simulation. Fig. 5 shows and explains the spatial organisation of abstraction points in the Ethiopian model.

3.3. Presenting pathways

In MCM interviews, stakeholders were asked to review the pathways by examining posters, pamphlets and presentations. Some sectors were represented by individuals and some by groups, as in Table 2.

This study was focused on testing how far our method could elicit convergent and divergent opinions from various social groups. Therefore, participant selection was opportunistic within purposive strata, aiming to gain perspectives from specific groups. We comment on ways this could be refined in the discussion.

Information on each pathway was presented in nine areas:

1. Functions groundwater is used for
2. Stage of development of the pathway in the basin and extent of exploitation of groundwater
3. Viable technologies
4. Ownership, governance, management and payment
5. Legal aspects of land and water use
6. Policy alignment
7. Implications for the poor
8. An image characterising the pathway (see Fig. 6 and Supplementary Material 4)
9. Results of the groundwater model showing extent of groundwater drawdown if this pathway was implemented for 5 years, in a choropleth and a cross-section (see Fig. 6 and Supplementary Material 4)

3.4. Multicriteria mapping of groundwater development pathways

Having reviewed the pathways, participants used MCM to express their own or their group's opinions on each. MCM is a systematic way to gather opinions of several participants on contrasting pathways (Coburn et al., 2018; Stirling, 2008). Facilitators guided participants on use of a software package, within which they firstly defined their own criteria for comparing Groundwater Development Pathways, then used those criteria as the basis for rating the pathways. Each pathway was given a score based on each criterion. When scoring, participants were asked to: (i) consider giving a range of scores for each option under each criterion, relating to the potential performance of that option under conducive and difficult conditions ('optimistic' and 'pessimistic' scores), and (ii) explain in a qualitative note why they had given each score, and under which conditions pessimistic and optimistic scores occur. For example, they could suggest variations on ownership models which would alter the equity dimensions of each pathway. This provided insight into their preferences in situations of ambiguity, contingency or uncertainty. It also provided them with an opportunity to relate any of the local knowledge of their context they had used to inform their score, in combination with the scientific knowledge presented to them.

When sets contained multiple people, dialogue between them was recorded in qualitative notes, stating whether consensus was reached, or recording continuing differences of opinion. Pessimistic and optimistic scores also provide an opportunity to explore and record heterogeneous opinions within the group. This process provides further routes to considering and capturing diversity of opinion rather than forcing convergence; it also reveals intragroup heterogeneities that can provide the basis for future disaggregated analysis.

Having completed scoring, participants were asked to 'weight' or define the relative importance of each of the criteria they used to rate the pathways. This resulted in a range of comparative rather than numerical scores for each pathway.[4] An example of the format is shown in Fig. 7. Participants reviewed this graphic and amended scores until the relative position of each pathway reflected their opinions accurately.

To facilitate cross-basin analysis, we defined three compulsory criteria participants should use in their rankings: Environmental Sustainability, Equitable Access and Ease of Operation and Maintenance. Predefining criteria dilutes the agency MCM lends participants, but this was considered a worthwhile trade-off as it facilitated comparison across contexts. Furthermore, it did not preclude stakeholders from redefining these 'proposed' criteria or adding their own. In Ethiopia and Tanzania, we added a workshop component, where we combined all data collected from different group interviews into one composite chart, which was displayed to stakeholders alongside individual charts, to promote discussion (Similar to Fig. 8).

3.5. Analysing MCM data

MCM data analysis involves clustering participant sets, pathways and criteria, and combining the separate participant sets' scores into composite charts. Comparing scores attached to different clusters shows which option is preferred by which combination of stakeholders, based on which criteria. Indication of 'favoured' pathways is rarely conclusive. MCM software calculates 'mean' scores for participant clusters, whilst recording highest and lowest scores any single participant set gave.

[4] The algorithms used by the MCM programme to assign positions on the x axis of a chart such as Fig. 7 can be found in Coburn et al., (2018), p.117.

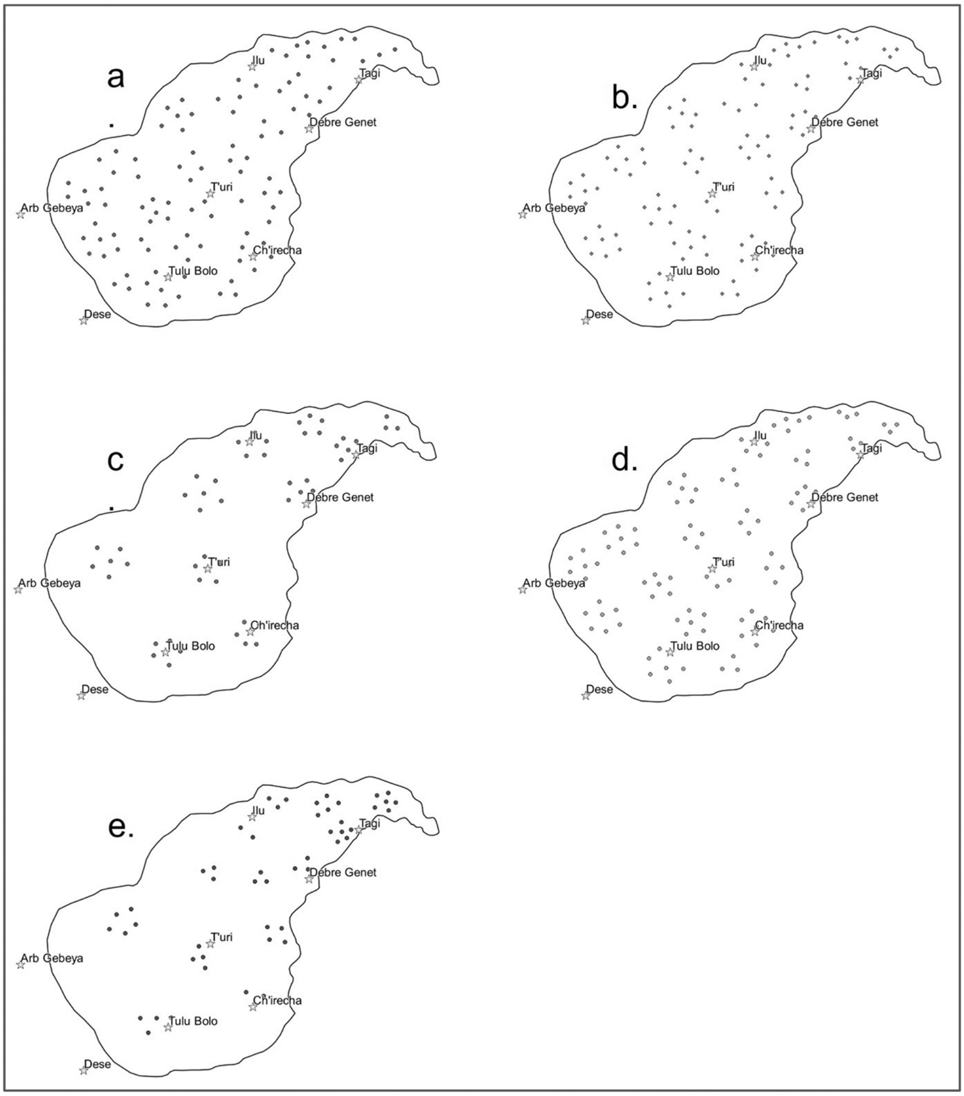

Fig 5. a-e: Proposed (hypothetical) spatial arrangement of abstraction wells within the Upper Awash Basin of south-central Ethiopia used in the modelling of scenarios: (a) Large-scale agriculture – water points abstracting 50 m^3/hour were placed in locations where irrigation was possible (model run in a hypothetical deep aquifer layer); (b) Medium-scale agriculture and medium-scale livestock – water points abstracting 15 m^3/hour were placed in locations where irrigation and livestock husbandry was possible was possible (model run in a hypothetical shallow aquifer layer); (c) Medium-scale multi-use – water points abstracting 15 m^3/hour were located in settlements (shallow aquifer); (d) Small-scale agriculture – water points abstracting 10 m^3/hour were located around settlements (shallow aquifer); and (e) Small-scale multi-use – water points abstracting 5 m^3/hour were located in settlements (shallow aquifer).

Composite output charts show both the range of 'means' and the 'extrema' of a cluster of participants: an example of the format is given in Fig. 8. Qualitative data are linked to the charts.

MCM also produces output charts showing how different participants and groups weight or prioritise different criteria (example in Fig. 9).

4. Results

4.1. Pathway ranking

We were interested in different participants' preferred pathways and prioritisation of various criteria. The first stage of MCM analysis assessed why different participant groups preferred different pathways. We clustered participants by country, by sector, and by scale. In Table 3, the pathway with the highest mid-point of its 'means' score band (see Fig. 7) is represented as the 'preferred' pathway for each cluster; that with the lowest mid-point is the 'least preferred', and so on. In all configurations, multi-use pathways are preferred to single-use pathways, and small- and medium-scale pathways are preferred to larger scale.

The following sections use qualitative data to understand reasons for these patterns, and present participants' suggestions of how the pathways would manifest in their contexts. As we aim to understand convergent and divergent opinions on pathways, the analysis is organised by grouping together pathways which performed similarly.

4.1.1. Low-scoring, larger-scale, agricultural pathways

4.1.1.1. Large-scale agriculture. There were ubiquitously low opinions of this pathway. Participants noted the comparatively heavy drawdown that would occur, and its negative effects on environmental sustainability and groundwater availability for other users. The lowest pessimistic scores reflected assumptions that irrigators would be unconcerned with other users' needs. Ethiopian respondents recognised that drawdown in the deeper aquifer would impact the upper aquifer over a period of decades because of imposed vertical drainage. Another inequitable aspect of this pathway was that only the richest could afford the requisite large-scale investment. There were also concerns about large-scale non-organic farms polluting and salinizing water and soil.

This large-scale pathway was perceived to contradict national policies aiming towards equitable development. Participants were concerned that pollution and extensive drawdown would outweigh economic benefits, with an Ethiopian academic participant saying: *'It's hard to mitigate these negative effects'*. They also mentioned that environmental sustainability was a policy imperative: '*… government always asks that every project implemented should be environmentally safe. This is the case for example when building dams'*.

However, this pathway's potential contribution to national revenue and job creation was recognised. The point was repeated in the optimistic score section that negative effects could be offset with appropriate

Table 2
List of stakeholder sets.

Country	Group number	Description
Tanzania	1	A national level water policy official (male (m))
	2	A national level agricultural policy official (female (f))
	3	A group of district level agriculture and water policy implementers (1 f, 3 m)
	4	A group of local users of groundwater for domestic purposes (2 m)
	5	A district level livestock officer (f) with a herders' representative (m)
	6	A local groundwater irrigator (m)
	7	A representative from the Southern Agricultural Growth Corridor of Tanzania project (m)
Ethiopia	8	A national level water policy official (m)
	9	A national level agricultural policy official (m)
	10	A group of district level agriculture and water policy implementers (m)
	11	A group of local groundwater irrigators (m)
	12	A group of local users of groundwater for domestic purposes (m)
	13	An academic (m)
	14	A representative from a national level development-focused NGO (m)
Niger	15	A national level water policy official (m)
	16	A group of national level livestock policy officials (2 m)
	17	A group of district level agriculture and water policy implementers and local government officials (1 f, 3 m)
	18	A group of local groundwater irrigators (2 f, 2 m)
	19	A representative from a national level agriculture-focused NGO (m)

management or employment of highly skilled staff, e.g. *'If proper siting principles are followed, there should not be a negative effect on other water users'* (Tanzanian district policy actors). It was considered that inequity could be prevented if enterprises were willing to share their water with other groups. The Nigerien state water policy actor suggested state management of large-scale enterprises would make them more equitable.

4.1.1.2. Medium-scale agriculture. This pathway could be called the second least favoured. Development actors rated it weakly, perceiving it as environmentally unsustainable, with high drawdown and agricultural pollution, and technically difficult, not offset by high economic gains.

Participants recognised this pathway entailed slightly less drawdown than the large-scale pathway. Some perceived the impact of a few, regulated, wells would be less negative than that of many unregulated wells, as in the small-scale multi-use pathway. Participants also highlighted that the extent to which positive and negative effects were realised depended on strict implementation of regulations such as for siting wells, obtaining water permits, restricting abstraction or conducting impact assessments. Nigerien participants considered that environmental auditing, already applied to centrally managed irrigation schemes, could mitigate negative impacts. They proposed that this pathway could be implemented more equitably by distributing water along canals, although drawdown effects would still disadvantage those with individual shallow wells close to such systems. Interestingly, participants did not cite the gender effects observed in earlier fieldwork, where those with plots further from the canal head – often women – were disadvantaged.

The requirement for skills and resources farmers lacked was frequently mentioned. For example, the national agricultural policy actor in Ethiopia stated: *'Since the operation is advanced, it may force to recruit well trained permanent expert, which creates job opportunity'*. But simultaneously, the national level water policy actor commented: *'Can be operated by young members of farmers' family'*. Medium-scale agriculture was therefore conceptualised not only as corporate, but an activity to which small-scale farmers may graduate.

4.1.2. High-scoring, smaller-scale, multi-use pathways

4.1.2.1. Small-scale multi-use. The small-scale multi-use pathway scored highly for the same reasons the large-scale pathway scored poorly. People perceived that low abstraction rates meant water users would not compete, making access equitable. Policy makers and development actors considered this pathway more community-appropriate and simpler to operate and maintain. An Ethiopian development professional commented: *'It is easy to use and source materials and skills required. It is mostly affordable and accessible'*.

Despite this being possibly the most preferred pathway, there were concerns about water quality and health implications of siting unprotected wells close to latrines, particularly in Niger and by water users and water policy actors. A local government participant considered poor quality water could not be considered 'available', pointing out different water qualities were appropriate for domestic and irrigation purposes. There were concerns that large numbers of unregulated small wells could eventually lead to unsustainable drawdown. Additional labour requirements for women and the young were another concern, as was inherently low economic productivity.

4.1.2.2. Medium-scale multi-use. This pathway could be considered the second favourite. Many participants thought a central community or municipal organising group could easily manage a groundwater abstraction and distribution facility effectively and responsibly. They considered that a municipal facility would not be sited close to latrines, as small-scale multi-use water points can be, thereby safeguarding water quality. Though there was some concern in Niger over the extent of national coverage, and overall about the ability of the less wealthy to pay charges, participants mentioned discount schemes implemented by municipalities for the elderly and poor.

Challenges of central management were noted: many recognised that municipalities could be slow to respond to maintenance and quality problems. Local domestic water users in Ethiopia noted that, if community management was required: *'This needs community involvement that has a collective action issue. It lacks defined ownership and control'*.

Local water users rated this pathway particularly highly, giving highest scores for ease of operation and maintenance, availability, community appropriateness and economic factors. For this group the advantages of centralized management outweighed the disadvantages. Users of groundwater for domestic purposes in Ethiopia commented that: *'Since this is a municipal service, there is an organized body that regularly look over it. It can be easily maintained and operated,'* adding *'This is communal infrastructure which many people can access and use with less cost'*.

4.1.3. Medium-scoring, smaller-scale, single-use pathways

4.1.3.1. Small-scale agriculture. Small-scale agriculture scored reasonably well but was not a preferred pathway for any group. It was perceived to have minimal drawdown effects, with appropriate technology entailing easy operation, enhancing viability for women and youth. A National Agricultural Policy actor from Tanzania noted: *'O and M is required for the pump, storage, irrigation infrastructure and delivery and application technologies. But the type of required maintenance is not complicated, because the technologies and required maintenance are less complicated',* while in Ethiopia, a group of district policy actors observed: *'Requires less human labour to extract water resulting in decrease workload to women and youth'*.

Participants discussed the costs of equipment, and returns, and some perceived this pathway as potentially economically fruitful, depending on crops selected. This has a policy advantage, hence the particularly high score (96 %) from the Ethiopian national scale policy actor: they perceived that it aligned with the Ethiopian Growth and Transformation Programme.

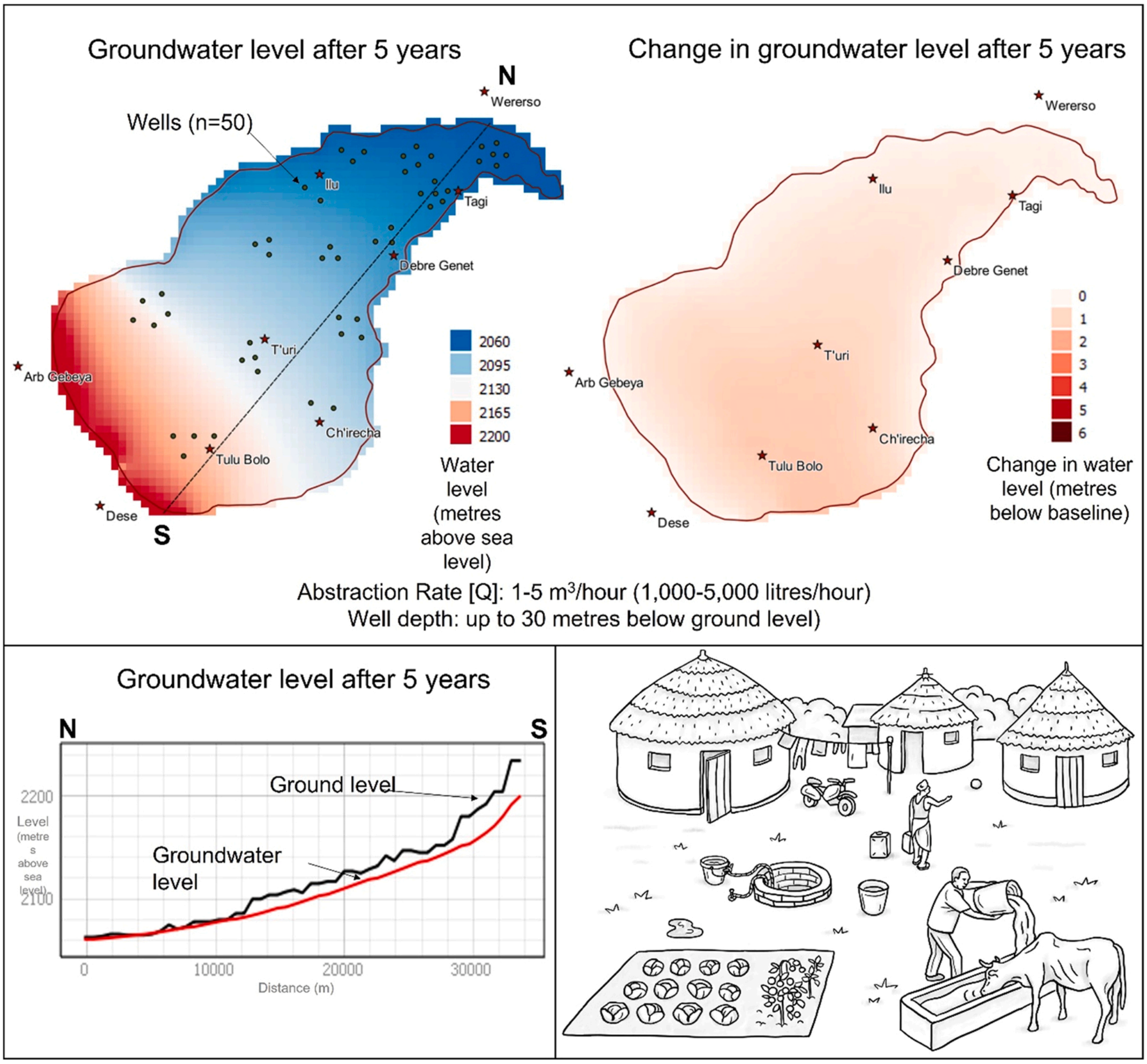

Fig. 6. Examples of choropleths and cross section showing change in groundwater levels after five years, and image, shown on posters and pamphlets for Ethiopia representing the 'small-scale multi-use' pathway.

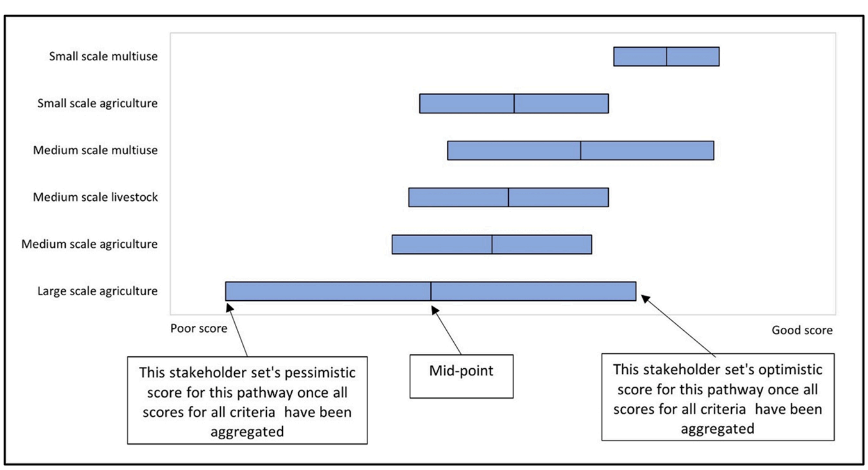

Fig. 7. Annotated example of a score chart, produced by the Tanzania local policy stakeholder set.

However, pessimistic opinions about this pathway acknowledged environmental pollution could occur if siting regulations were ignored, and it was less accessible to the poor and landless, and less profitable. National livestock policy actors in Niger noted there was a chance individuals could perform small-scale commercial agriculture in agro-pastoral zones, which the law forbade, and they deemed inappropriate

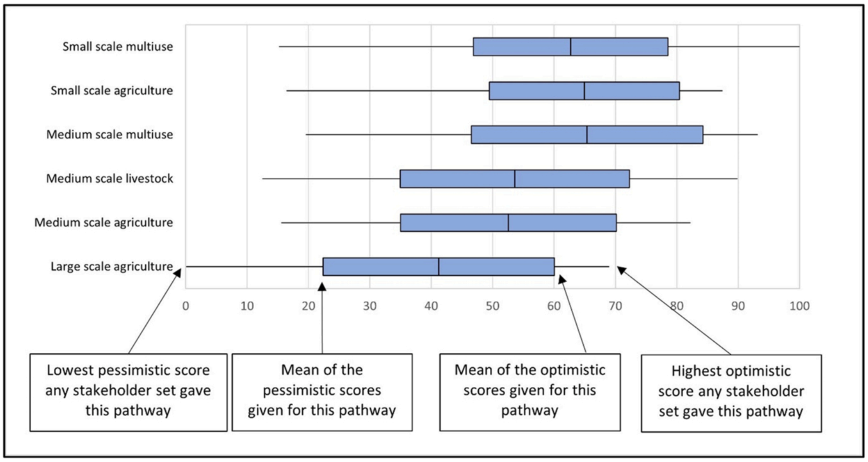

Fig. 8. Annotated composite ranks chart combining data from users of groundwater in all three observatories.

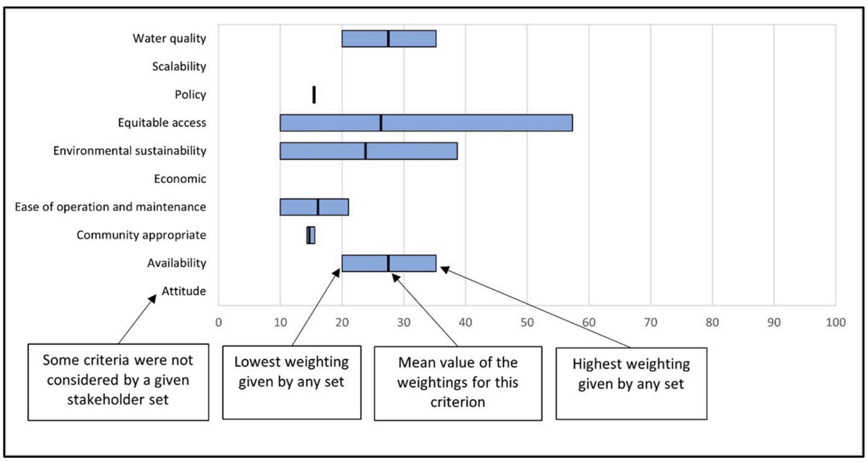

Fig. 9. Annotated composite weights chart for all Nigerien actor groups.

due to a low water table.

4.1.3.2. Medium-scale livestock. The medium-scale livestock husbandry pathway generally scored poorly, but was the pathway most favoured by the sole academic stakeholder, as it was aligned with national policy priorities and in their opinion therefore had potential to be well supported, profitable, scalable and non-polluting: *'In my opinion, government and regulatory bodies would be happy to scale up all of these pathways as far as possible'*.

Participants opined that profitable facilities would invest in operation and maintenance, and a larger scale, regulated facility would likely be able to manage nitrate pollution around a point source. Yet, simultaneously, development and policy actors concurred that this pathway required specific skills and high investment, and was not appropriate everywhere. As Ethiopian national water policy actors observed: *'Requires some level of education and may not be scaled up in many places'*.

In Niger this option of private ranching, involving pastureland enclosure and groundwater appropriation, was considered less equitable than traditional transhumant pastoralism. Nevertheless, development actors considered that traditional pastoralism was becoming less viable, and there was therefore a future for some type of ranching, although this was not current policy.

4.1.4. Pathway combinations

In MCM interviews, participants compared pathways. Yet, workshops revealed they were more convinced by the more realistic scenario of multiple, intertwined Groundwater Development Pathways existing in a landscape. There was demand for more precise models, showing how the spatial arrangement of multiple sets of abstraction points, pumping at different rates, would influence aquifer dynamics. Stakeholders appreciated the location of the Tanzanian and Ethiopian models in the geology of the area, rather than the generalised model environment presented in Niger.

4.2. Criteria

The second stage of our analysis involved understanding participants' weighting of the various criteria, including analysis of the relationships people perceived between them. 17 criteria were proposed by participants in addition to the three specified by the research team. These were clustered as shown in Table 4.

In Table 5, 'availability', 'quality' and 'environmental sustainability' are never 'least favourite' criteria. The group of district level policy implementers in Tanzania commented that: '*Environmental sustainability is important because if there is massive environmental destruction, none of the other considerations are possible*'.

These heavily weighted criteria strongly influenced the ranking of pathways, and very high or low scores were usually for the interlinked and prioritised criteria of environmental sustainability, availability and quality, as well as equitable access, policy fit, and ease of operation and maintenance.

Some participant notes show the dominance of a specific criterion,

Table 3
The preferred and least preferred pathways of each stakeholder groups (groups as in Table 1).

Cluster *(groups)*	Preferred pathway	2nd preferred pathway	Least preferred pathway
All data combined	Small-scale multi-use	Medium-scale multi-use	Large-scale agriculture
By country			
Ethiopia	Small-scale multi-use	Small-scale agriculture	Large-scale agriculture
Tanzania	Medium-scale multi-use	Small-scale multi-use	Large-scale agriculture
Niger	Small-scale multi-use	Medium-scale multi-use	Large-scale agriculture
By sector			
Policy (sets 1, 2, 3, 8, 9, 10, 15, 16, 17)	Small-scale multi-use	Medium-scale multi-use	Large-scale agriculture
Development (sets 7, 14, 19)	Small-scale multi-use	Small-scale agriculture	Medium-scale agriculture
Academic (set 13)	Medium-scale livestock	Small-scale multi-use	Large-scale agriculture
Water user (sets 4, 5, 6, 11, 12, 18)	Medium-scale multi-use	Small-scale agriculture	Large-scale agriculture
By level			
National (sets 1, 2, 8, 9, 13, 14, 15, 16, 19)	Small-scale multi-use	Small-scale agriculture	Large-scale agriculture
District (sets 3, 7, 10, 17)	Small-scale multi-use	Medium-scale multi-use	Large-scale agriculture
Local (sets 4, 5, 6, 11, 12, 18)	Medium-scale multi-use	Small-scale agriculture	Large-scale agriculture

such as '*The top priority is equitable access for all*' (National Water Policy actor, Tanzania). Yet, more comments point to connected concerns. For example, the Ethiopian Development actor connected environmental sustainability and equitable access, saying: '*Equity should be the most important criterion to ensure sustainable use of water and it should be inclusive to avoid conflicts in use of the natural resource*' and the district level policy actors in Tanzania said, '*Actually, all the criteria are interdependent, interrelated*'.

5. Discussion

Results on actors' priorities and preferences, and on divergence and convergence between groups' opinions, enable us to relate the pathways approach to contemporary issues on groundwater development, management and governance. These have implications for how MCM and the pathways approach may be used in future to analyse groundwater development.

5.1. Development, sustainability, and contingency

Governments and development agencies face choices about whether and how to exploit aquifers across Africa, which have been suggested as an important yet underexploited source of freshwater (Cobbing and Hiller, 2019). Any such development would depend on 'secondary factors' such as energy availability and cost, availability of local information e.g. about regulations, and availability of capital/ credit (Cobbing and Hiller, 2019). But the implications of such development depend on context-specific hydrogeological factors such as transmissivity; climate change, particularly the frequency and periodicity of intense recharge events; and sociodemographic demand (Cuthbert et al., 2019; MacDonald et al., 2021; Taylor et al., 2013). In some cases, e.g., instances of recharge from intensified rainfall, the benefits of rapid development may outweigh risks of aquifer depletion (Gaye and Tindimugaya, 2019; Cobbing and Hiller, 2019). In other cases, for example of fossil groundwater, aquifer depletion by some actors may be unacceptable to others (MacDonald et al., 2021; Taylor et al., 2013). The research showed that a combination of MCM and modelling could help present the specific conditions of an aquifer to stakeholders, and help them

Table 4
Criteria proposed by researchers and participants.

Proposed by	Group of criteria	Criterion name	Definition
The research team – considered by all participants	Environmental sustainability	Environmental sustainability	How far environmental integrity is preserved across space and time as humans use groundwater. This criterion includes integrity of landscape and ecosystem functions such as land cover, biodiversity and soil quality, and maintenance of important biomes such as. wetlands. This consideration is mainly in relation to water quantity, but also considers water quality, and effects of environmental destruction on human health.
	Ease of operation and maintenance	Ease of operation and maintenance	How well the groundwater abstraction, distribution and storage equipment can be used and kept in good working order. This considers cost and knowledge implications, but also institutional and organisational arrangements.
	Equitable access	Equitable access	How far the pathway guarantees fair and equal ability of all social groups (for example women and men, young and old) to access groundwater as they need. This considers physical factors such as distance to/ depth of a water source. It also includes any other economic and social factors which may influence someone's ability to gain access to groundwater, such as infrastructure and regulation.
Tanzania district level livestock officer and a herders' representative	Availability	Availability of groundwater	This relates to how technically available groundwater is in the pathway taking into account depth and infrastructure, before considering political and administrative constraints on availability.
Niger national level livestock policy officials		Availability	
Tanzania national level water policy official		Availability	
Niger district level agriculture and water policy		Actual availability	

(*continued on next page*)

Table 4 (*continued*)

Proposed by	Group of criteria	Criterion name	Definition
implementers and local government officials			
Ethiopia national level water policy official	Attitude	Attitude	This relates to how likely the community are to invest in pathways
Niger national level water policy official	Community appropriateness	Appropriate technology	These criteria relate to how affordable, comprehensible and operatable the technology is for all members of the community where it is installed.
Niger local groundwater irrigators		Appropriate technology	
Niger national level agriculture-focused NGOs		Appropriate technology	
Ethiopia local users of groundwater for domestic purposes		Appropriate technology	
Ethiopia district level agriculture and water policy implementers		Knowledge and skill	
Tanzania representative from the Southern Agricultural Growth Corridor of Tanzania project		Social Inclusivity	
Ethiopia academic	Economic	Cost-benefit balance	These criteria are all to do with economic or financial gain or profitability from groundwater use
Tanzania national level agricultural policy official		Economic return	
Tanzania local users of groundwater for domestic purposes		Economic benefits	
Ethiopia district level agriculture and water policy implementers		Economic benefits	
Tanzania national level water policy official		Economic benefits	
Tanzania local groundwater irrigator		Economic benefits	
Ethiopia national level agricultural policy official	Policy	Policy direction	These criteria are all to do with how far a pathways fits with national but also local and international policy imperatives.
Niger national level agriculture-focused NGOs		Policy alignment	
Tanzania district level agriculture and water policy implementers		Policy fit	
Ethiopia national level water policy official	Scalability	Scalability	These criteria relate to how possible it would be to implement a pathway across a large area, regionally or nationally
Ethiopia representative from national level development-focused NGO		Scalability	
Ethiopia academic		Technical scalability	
Niger national level livestock policy officials	Water quality	Water quality	These criteria refer to the effects of a pathway on water quality – despite overlaps with the 'environmental sustainability' criterion, participants wanted additional criteria that related to human health consequences of inadequate water quality.
Niger district level agriculture and water policy implementers and local government officials		Water quality	

analyse any trade-offs inherent to abstraction.

Study participants appreciated the potential of groundwater, yet in these basins agreed nearly unanimously in their concern about the environmental sustainability of exploitation. Participants highlighted the complexity of questions about sustainability by explicitly connecting this to availability. They also recognised that these concerns were inflected by the actions of different actor groups and power relations between them: awareness was shown that use of groundwater, an invisible resource which is problematic to monitor and govern, by one often powerful group, could affect groundwater levels and quality, inequitably affecting others' use (Hoogesteger and Wester, 2015). These considerations informed the lower scores for agricultural and livestock pathways relative to multi-use pathways.

Lower scores for larger scale pathways therefore show participants' awareness that environmental outcomes and availability are often contingent on the behaviour of larger scale, more powerful actors. Large-scale pathways have sometimes been associated with land acquisitions or even 'land grabs', which are also ultimately 'water grabs' (Dell'Angelo et al., 2018; Mehta et al., 2012), particularly pertinent to the Awash basin (Bekele et al., 2022). Some participants also reflected that system outcomes (e.g., water quality in unprotected wells) were contingent upon policy adherence (e.g., correct siting of wells). Policy adherence is therefore not only a criterion in itself but also a factor determining performance in terms of other parameters. These connections showed participants' appreciation of the contingency inherent in groundwater systems.

5.2. Governance, management and scale

In terms of specific policy and management approaches, IWRM has come to dominate in the study contexts, and participants concurred that governance and management should transcend sectors such as health, agriculture, and domestic uses of water. CBWRM has been used within IWRM to achieve environmental sustainability and equity, combined to various extents with state-led and private-sector approaches (van Koppen et al., 2007). Participants considered that communal or municipal facilities are better managed than individual enterprises, more capable of managing the environmental threats of excessive drawdown or pollution, and potentially more equitable. Simultaneously, they acknowledged that small-scale privately-owned facilities are affordable, even for the poor, and can be more rapidly and easily maintained than expensive and bureaucratic centrally managed systems. These ideas highlight that effectiveness of governance, management, operation and maintenance, and the implications of different governance systems for different groups, depend on implementation style and the level at which facilities are managed (Zwickle et al., 2021).

Table 5
Prioritisation of criteria: all weights given as a percentage. Weight = 100 % means weighted as maximally important by all participants; weight = 0 % means not considered by any participants.

Cluster *(groups)*	Most important criterion	Second most important criterion	Least important criterion	Uncounted criteria (weight=0)
Overall	Quality (27.5)	Environmental sustainability (27.2)	Attitude (5.0)	None
By country				
Ethiopia	Community appropriate (34.9)	Policy (31.9)	Attitude (5.0)	Availability, Quality
Tanzania	Policy (33.3)	Availability (26.1)	Ease of operation and maintenance (20.9)	Attitude, Scalability, Quality
Niger	Availability, Quality (27.5)	Equitable access (26.2)	Community appropriate (14.7)	Attitude, Economic, Scalability
By sector				
Policy	Policy (32.6)	Economic (28.7)	Scalability (4.2)	None
Water user	Availability (34.8)	Equitable access (31.6)	Economic (20.2)	Attitude, Policy, Scalability, Quality
Development	Environmental sustainability (31.3)	Equitable access (25.0)	Policy (15.4)	Attitude, Availability, Economic, Quality
Academic	Environmental sustainability (32.0)	Economic (24.0)	Scalability (12.0)	Attitude, Availability, Community appropriate, Policy, Quality
By level				
National	Environmental sustainability (30.7)	Economic (28.0)	Attitude (5.0)	None
District	Availability, Quality (35.0)	Policy (33.3)	Equitable access (15.0)	Attitude, Scalability
Local	Availability (34.8)	Equitable access (31.6)	Economic (20.2)	Attitude, Policy, Scalability, Quality

Water users preferred the medium-scale communally or municipally managed multi-use pathway to the smaller-scale multi-use pathway, as responsibility was deemed to be collective rather than individual. They saw a role for water governance, policy implementation and management at the scale beyond the community (Smits et al., 2015). Policy and development actors preferred the small-scale pathway. A cynical view would be that each actor wanted the other to take responsibility for water management (Whaley and Cleaver, 2017). A more prosaic reading is that water users' opinions were informed by first-hand experiences of laborious individualised, manual well construction, operation and maintenance – which qualitative data showed may be especially onerous for women. Many of these participants may also have had comparatively more positive experiences of municipalities, especially urban ones, taking responsibility for domestic water supply. These actors advocated a community 'plus' approach, where communities are supported in the long-term towards positive outcomes by an external agency, preferably with local administrative connections (Hutchings et al., 2015, 2021).

Our pathways were not specific about the permitting systems each implied, or how functional licensing regimes would be. In the study contexts, small-scale domestic use in particular was often carried out with no licensing or permitting, and the small-scale pathways were compatible with self-provision or farmer-led irrigation development (Woodhouse et al., 2017; Shah et al., 2020). As in many parts of Africa, contemporary norms of access to water in these pathways are often rooted in traditional or customary entitlements (García et al., 2017). Appropriate governance systems depend on how renewable groundwater is (Foster and Ait-Kadi, 2012; Foster and Shah, 2012; Villholth, 2018). Shah et al. (2020) suggest that such local, informal forms of governance may develop more spontaneously in slowly recharged aquifers, making their exploitation less problematic. Our participants expressed preferences for small-scale pathways, without stating they should be licenced or regulated, or identifying that different recharge rates may imply different appropriate forms of governance. Yet, when analysing larger scale systems, they said policies and management regulations should be followed to support equitable and sustainable use.

Authors have noted that current permitting situations rarely reflect historical realities, are not necessarily effective at protecting from either pollution or over-abstraction and are rarely enforced in the absence of strong institutions (van Koppen et al., 2014). Indeed, governance instruments are weakly developed in the study contexts, as they are at early stages of groundwater development (Koundouri et al., 2017). Although participants considered that regulation of large-scale abstraction would have positive environmental implications, there was recognition that ineffective governance leads to pessimistic, inequitable situations in which some needs or preferences may not be met. Although participants did not express opinions on permitting regimes, their acceptance of small-scale pathways regulated by traditional norms, and large-scale pathways when effectively regulated, may show acceptance of hybrid permitting regimes, as suggested by Schreiner and van Koppen (2020). This acceptance of different governance arrangements for different, potentially simultaneous, pathways suggests combinations of various governance arrangements for diverse types of user may continue to be appropriate. These varying arrangements may be thought of in terms of water tenure, as they relate to the relationship between water users (Hodgson, 2016). Future work should explore governance implications in more detail and consider different modes of governance as pathways.

5.3. *Diverse pathways, divergent priorities, ambiguity and certainty*

Participants appreciated the validity and interconnectedness of multiple diverse water uses. This reflected water users' reality of using water in multi-functional ways, as widely recorded across Africa in literature (van Koppen et al., 2020) and as informed our characterisation of the small and medium-scale multi-use pathways. For policy makers, this appreciation may reveal their familiarity with the IWRM concept, emphasising multiple water uses and sources (Savenije and Van der Zaag, 2008). In the Tanzania workshop, national policy actors stated it was more appropriate to acknowledge a variety of activities takes place simultaneously in the landscape (Butterworth et al., 2010), informing planning for multi-use water development. Tanzanian participants expressed interest in seeing model simulations of the effects of a combination of the presented pathways.

The pathways were deliberately broad, to reflect the variety of possible implementation strategies in each context and the contingent nature of decision-making under these scenarios. Thus, our groundwater modelling represented a comparative impression of the relative effects of different pathways, rather than a certain prediction of drawdown. Participants considered such ambiguity unproblematic and realistic. Yet, they expressed a desire for greater quantitative certainty about impacts on the water table than a basin level model could meaningfully provide for such ambiguous scenarios. This points to the need for careful consideration of the role of modelling in decision-making about uncertain futures.

A pathways analysis therefore revealed participants' awareness of the contingent nature of the outcomes, and of the complex ways that issues including sustainability, equity and availability interacted. It also showed that futures or multicriteria analysis exercises should provide participants with the opportunity to analyse realistic, complex and multicomponent futures, which may be ambiguous. Yet, there needs to be more data and as much certainty as possible about the implications of each component of these futures.

As land area under irrigation expands in Africa, alongside increased demand for domestic and industrial water, groundwater use is projected to expand. Policy actors will need to make decisions about which Groundwater Development Pathways are more viable in their context, taking convergent and divergent stakeholder opinions into account. Here, a mixture of MCM and modelling was able to elicit convergence in opinion between diverse groups who were concerned about environmental sustainability and availability, and differences between groups in term of their preferences for management. These methods can be developed in future work. The pathways framework's considerations of sustainability, equity, contingency and uncertainty also provide a helpful lens through which to analyse groundwater development.

5.4. Using MCM and groundwater modelling within pathways frameworks

Findings indicate tensions between using broad pathways, which provided room for site-specific interpretations, and mobilising physical/spatial modelling. Participants expressed interest in more specific groundwater models to predict spatialised drawdown effects of specific constellations of wells with different capacities. When such modelling is based on detailed field observations or user knowledge, it can quantity effects of drawdown in a way meaningful to stakeholders, but the pathway it represents would have to become much narrower. Stakeholders should also understand the uncertainty inherent in the model. With these caveats, it seems promising to use more participatory and site-specific modelling in combination with multicriteria analysis approaches. Practically, this suggests developing flexible, representative models, based on local observations of practice and geology, and possibly more detailed 'stress-testing' of environmental change effects (e.g., climatic or land cover change).

Having shown that MCM is able to elicit divergent opinions of different groups about pathways, attention can also now be paid to complicating the method to make results more relevant. One aspect of this is to present multiple, more complex pathway combinations. For example, reproductive use of shallow groundwater should be modelled as taking place alongside most other scenarios, as interactions between this and other mode of water use are highly relevant. Combinations of low abstraction pathways could work together to produce a pathway of medium abstraction. Future modelling can also use longer timescales (10–20 years), which could account for the impact of less frequent major recharge events, which are important in determining the sustainability of groundwater resources (Cuthbert et al., 2019).

More attention can also be paid to participant selection. This project insufficiently represented women water users' perspectives, and due attention should be paid to the gender composition of groups in future work. Researchers should also consider the specific characteristics of an intersectional identity that may influence participants' responses, rather than claiming homogeneity of a group or representativeness of a specific interviewee. Qualitative data help understand the range of opinions in a group. When qualitative comments indicate heterogeneous intragroup opinions, iterative analysis can disaggregate groups to explore these and ensure a range of relevant groups are included. For example, 'irrigator' categories could justifiably be disaggregated by operation size; 'domestic water user' categories could be gender disaggregated. As the analysis process clusters groups together, heightened attention should be paid to which disaggregated groups contributed pessimistic and optimistic scores and comments. Future work can also work to integrate participants' knowledge more holistically, for example by interrogating local knowledge of aquifers and environmental change, possibly even as input into models.

Although MCM shows promise for helping various stakeholders, such as policy actors and diverse water users, understand and discuss each others' perspectives, it requires expertise to perform, as the application of pessimistic and optimistic scenarios can be fraught. A disconnect occasionally appeared between qualitative and quantitative data when MCM participants were invited to allocate differing 'pessimistic' and 'optimistic' scores, in instances when they considered a change in context may strongly influence the outcome of a pathway. In several instances, divergent optimistic and pessimistic scores were given, yet the associated comments did not identify what was responsible for the uncertainty, sometimes simply describing advantages and disadvantages of a pathway.

It may be that these divergent scores reflected a general uncertainty about outcomes in this context or represented differing opinions within the groups. Facilitators need a high level of skill and experience, and adequate time, to unpick the meanings behind these scores. They can also adapt the MCM process to minimise these challenges. Though uncertainty and contingency are important central concepts, it may be prudent to introduce consideration of uncertainty at a later stage or make this optional. Facilitators may designate initial scores as 'optimistic', only adding pessimistic scores should a precise source of uncertainty be identified. As full attention cannot be provided to every single MCM score, it is worth moving rapidly through the exercise to focus in depth on those where pessimistic and optimistic situations exist.

It may also be necessary to conduct more focused MCM processes targeting specific aspects of a system, e.g., governance or industrial strategy, and analyse the impacts of multiple pathways on other, specific predefined criteria. This would permit analysis of trade-offs, whereas pessimistic and optimistic scores provide opportunities to consider the impacts of sector-specific or general safeguards.

Many of the qualitative outputs of MCM could be obtained in a similarly systematic manner using a focus group or a matrix-scoring exercise. The advantage of MCM software is that it produces an output graphic which can be used to focus interviewees' attention and prompt an immediate review. Furthermore, it permits real-time comparison of different participants' perspectives that can facilitate discussions among them, as in our workshops. Considering interactions between pathways was as important as analysing their individual effects. It is therefore critical to devote time to discussion of synergies, in/compatibilities and conflicts between pathways, to bring considerations of complexities and contingencies to the fore.

Other modelling and 'game' approaches have successfully combined hydrological and socioeconomic components to model impacts of aspects such as policy compliance on aquifer levels (Varela-Ortega et al., 2011; Castilla-Rho et al., 2019). The advantage of MCM is that participants are prompted to consider their own and others' priorities in relation to less tangible social, economic, environmental and technological implications. When this is well connected to existing and emerging groundwater governance systems, there is potential to contribute to more responsive governance (Bellamy et al., 2013). Thus, when water managers and policy makers and implementers are involved, this may facilitate better informed, more equitable decision-making.

6. Conclusions

As groundwater becomes more widely used in tropical Africa, the possibility of conflicts over its use arises, as different development pathways may be differentially attractive to separate groups of stakeholders. Therefore, in this study, we sought to understand the priorities and preferences of these diverse groups, identifying points of convergence and divergence, eliciting perspectives on groundwater management and governance, and assessing how useful MCM could be as a tool in investigating areas of potential agreement and disagreement. Employing an interdisciplinary, multi-level research approach in three complementary ‘basin observatories’, the study gathered policy-relevant data relevant to tropical Africa.

Having examined simulations of drawdown impacts of different groundwater development pathways, participants’ preferences converged towards smaller-scale, multi-use pathways. They found the idea of somewhat ambiguous futures involving multiple co-existing pathways most realistic and appealing. Availability and environmental sustainability, encompassing water quality, were shared priorities across the groups in all three basins. Participants appreciated that the complexity of groundwater systems and their contingent nature meant activities involved in different pathways could impinge upon one another, with implications for equitable access and use. The smaller-scale, multi-use pathways favoured by participants are aligned more with IWRM policy than agricultural strategies aiming for intensification or large-scale farming.

Considering mechanisms that could achieve environmentally sustainable, equitable supplies of groundwater, policy and development actors preferred individual-scale management, which they perceived as potentially cheaper and more efficient. Yet, groundwater users considered community-level ‘plus’ governance systems most appropriate, as the longer-term water quality impacts of unregulated access posed an unacceptable health risk. This view may be less commonly expressed in policy contexts where discourses of marketisation or community- or individual-level responsibility hold sway. It may be appropriate to consider multiple governance arrangements for simultaneous, potentially conflicting groundwater development pathways. Although MCM requires expert facilitation to collect credible qualitative data, we found that it can systematically collect and analyse convergent and divergent opinions about complex, contingent systems, whilst acknowledging ambiguities and embracing uncertainty. Future research could combine MCM-style analysis with precise, situated groundwater modelling based on detailed local water use and hydrogeological observations. Participatory modelling, where stakeholders give input into abstraction scenarios, could assist policy makers to integrate stakeholder concerns, such as about water quality and the scale of management, into groundwater decision-making processes. As groundwater becomes a more important water source there will be increased need for such interdisciplinary, multistakeholder exercises to enhance understanding and support appropriate management and governance.

CRediT authorship contribution statement

Imogen Bellwood-Howard: Methodology, Software, Formal analysis, Investigation, Writing – original draft, Project administration. **John Thompson:** Conceptualization, Methodology, Software, Investigation, Writing – review & editing, Supervision, Funding acquisition. **Mohammad Shamsudduha:** Methodology, Software, Formal analysis, Investigation, Data curation, Writing – review & editing, Visualization, Project administration. **Richard G. Taylor:** Conceptualization, Methodology, Software, Writing – review & editing, Supervision, Funding acquisition. **Devotha B. Mosha:** Methodology, Investigation, Project administration. **Gebrehaweria Gebrezgi:** Investigation, Project administration. **Andrew K.P.R Tarimo:** Investigation, Project administration. **Japhet J. Kashaigili:** Investigation, Supervision. **Yahaya Nazoumou:** Investigation, Supervision. **Ouassa Tiékoura:** Investigation.

Declaration of Competing Interest

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

Data Availability

The data that support the findings of this study can be accessed through the FigShare repository using DOI https://doi.org/10.6084/m9.figshare.20738248.v1.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2022.09.010.

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