PLOS Water

RESEARCH ARTICLE

Community-led polycentric water management for drought mitigation in Southern Zambia

Carol Emma Mweemba[1*], **Barbara van Koppen**[2], **Giriraj Amarnath**[3]

1 International Water Management Institute, Lusaka, Zambia, **2** International Water Management Institute, Pretoria, South Africa, **3** International Water Management Institute, Colombo, Sri Lanka

* carolmweemba83@gmail.com

Abstract

Recurrent droughts in Southern Zambia have increased rural community vulnerabilities, intensified water scarcity, and worsened food insecurity. Unpredictable rainfall and the drying of open water sources pose significant challenges to livelihoods. In response, Hanzila community in Zambia implemented a transformative locally-led initiative to enhance drought resilience, with support from district-level authorities, national government, and international partners. Sectoral silos in the government's vertical polycentric decision-making framework were overcome by horizontal decision-making across all tiers. Accordingly, the installation of a solar-powered borehole facilitated year-round access to water for drinking, domestic use, livestock, and irrigation. An assessment of the impact of the solar-powered borehole established that 86% people had become less reliant on unclean water sources, with reduced travel to access water. Moreover, the proportion of households cultivating gardens increased from 23% to 69%, enhancing food security and nutrition. Over three quarters of the households that owned gardens now generated income from vegetable sales. The solar-powered borehole also created a reliable water source for 89% of the households that raised small livestock — goats, sheep, and chickens. Among the 48% of respondents who owned cattle, more than half had stopped using distant open water sources; instead, they now accessed water from the solar-powered borehole. However, households situated farther from the ten supply taps implemented with the borehole still had to travel longer distances to access water. To ensure all households have equal access to water when the available funding is limited, community members could contribute to finance the extension of the reticulation to reach all households.

OPEN ACCESS

Citation: Mweemba CE, van Koppen B, Amarnath G (2025) Community-led polycentric water management for drought mitigation in Southern Zambia. PLOS Water 4(12): e0000356. https://doi.org/10.1371/journal.pwat.0000356

Editor: Gebremedhin Gebremeskel Haile, Wesleyan University, UNITED STATES OF AMERICA

Received: February 4, 2025

Accepted: October 29, 2025

Published: December 2, 2025

Peer Review History: PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: https://doi.org/10.1371/journal.pwat.0000356

1. Introduction

With climate change and anomalous weather resulting in heavy rain or dry conditions, the availability of surface and groundwater resources is becoming uncertain.

Data availability statement: All data underlying the findings of this study "Community-led polycentric water management for drought mitigation in Southern Zambia" are available from International Water Management Institute (IWMI) and can be accessed at https://doi.org/10.5281/zenodo.17579285.

Funding: This work was funded as part of the Consultative Group on International Agricultural Research (CGIAR) Initiative on Climate Resilience. Funding support was provided through contributions to the CGIAR Trust Fund (https://www.cgiar.org/funders/) to CEM, BVK, and GA. To learn more about this Initiative, please visit https://www.cgiar.org/cgiar-research-porfolio-2025-2030/climate-action/. The funders had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors have declared that no competing interests exist.

Such events are becoming less predictable, and increasingly, there are more extreme events overall [1,2]. Countries in Southern Africa, including Angola, Lesotho, Malawi, Mozambique, Namibia, Zambia, and Zimbabwe, are in particular experiencing progressively severe and recurrent droughts. The droughts associated with the 2024 El Niño event had devastating impacts on livelihoods [3].

Addressing the impacts of droughts requires elements such as integrated resilient watersheds, natural storage facilities (i.e., perennial streams and ponds, lakes, and aquifers), human-made reservoirs, pumping and conveyance infrastructure, and nature-based recharge. Co-design and implementation of climate-resilient water infrastructure with local communities is vital [4]. Applying bottom-up approaches to adapt to climate variability ensures that measures fit the local context and can respond to problems experienced in rural communities [5,6]. Moreover, locally-led approaches build on the historical knowledge and practices of rural farm communities and pastoralists who have actively sought ways to adapt to climate variability [7]. Historically, these communities have used and developed surface and groundwater sources to meet their multiple domestic, livestock, and productive water needs [8]. When rural people design infrastructure, they acutely consider their multiple water needs in multi-purpose infrastructure. As social communities, they have also developed norms and rules to share limited water resources [9,10]. This customary or community-based water tenure is increasingly being recognised in global forums [11,12].

Locally-led climate adaptation mobilises communities' valuable existing technical, institutional, and social assets and knowledge of seasonal and perennial water resources and their availability. Engaging communities early in the project cycle is important to avoid the pitfalls of traditional top-down approaches [13,14]**.** Indeed, governments, NGOs, development banks, philanthropic organisations, and other water-development organisations increasingly recognise that such approaches are often costly and unsustainable. Community involvement is more effective in enhancing the sustainability of solutions to water management and climate change adaptation [15].

Insights and lessons learned from these bottom-up approaches are critical in this era of climate change [16,17]. They can inform initiatives by multi-tiered governments as well as the top-down global climate adaptation funds — such as green funds or loss and damage funds — and ensure that funds at the international and national levels reach the most vulnerable populations [17,18].

Best-practice solutions can strengthen and transform existing governance structures. The concept of polycentric water governance recognises the different nodes of decision-making that operate both horizontally and vertically [19]. Horizontal and vertical integration is especially significant for water resources, which inherently connect all tiers [19]. On the ground, integration is already being practised; within community-based water tenure, individuals and communities combine multiple surface and groundwater sources for multiple uses, often using multipurpose infrastructure. However, a significant challenge remains in achieving integrated adaptation pathways among governmental and non-governmental institutions [20]. The siloed approaches lead to parallel financing streams defined by top-down earmarked funding, such as for Water, Sanitation, and Hygiene (WASH), for irrigation, for drought resilience, for health, etc. [21,22]. This fragmentation hampers effective and unifying coordination and convergence in water governance measures.

In Zambia, droughts and water access are major challenges that affect social empowerment and sustainable development. In Southern Zambia in particular, rural communities are increasingly experiencing significant water stress due to the impacts of climate change [23]. In 2023–2024, extreme drought led to severe water scarcity during what should typically have been the rainy season. This critical lack of access to water increased the vulnerability of communities [24]. Before the 2023–2024 drought, 74.7% of the Zambian population had experienced improvements in access to water for drinking and domestic uses. However, this percentage subsequently decreased due to the drying of surface water sources and diminished groundwater availability [25].

Applying age-old local knowledge and resources in horizontal decision-making processes [26,27] — in tandem with connecting vertical and horizontal polycentric decision-making processes with support agencies — can facilitate community-led processes that build long-term resilience in the face of climate change [28]. Rural communities in Zambia have demonstrated remarkable ingenuity in adapting to the challenges posed by seasonal and recurrent climate variability [29,30]. When surface water sources such as rivers and ponds begin to dry up, these communities take proactive measures such as digging scoop holes in riverbeds to access the limited subsurface water. This water is used for drinking, domestic uses, livestock, and irrigation.

To effectively manage water scarcity, communities often establish normative rules that promote collaborative efforts [31–33]. Initially, when water supplies become limited, they tend to agree to suspend activities like gardening [34]. This ensures that essential needs are met first: drinking water, basic domestic use, and water for livestock [5]. Furthermore, these communities diversify their water sources to lessen their reliance on a single source. This reduces vulnerability to water shortages.

However, as the impacts of climate change escalate and extreme events become more frequent, these vital local coping mechanisms can prove to be increasingly inadequate [35]. To effectively tackle these growing challenges, there is an urgent need to significantly accelerate investments in improved, sustainable, and integrated water solutions. Such solutions must comprehensively address the diverse water needs of communities [36,37].

Such a transformative response to worsening climate vulnerability was implemented in Hanzila community in Monze District, Southern Province, Zambia [38,39]. Hanzila had been increasingly affected by the impacts of climate change (including altered rainfall patterns and rising temperatures), which had intensified drought conditions [38,40]. These changes resulted in reduced water availability, disrupted agricultural activities, and increased food insecurity [38,41], highlighting the urgent need for locally-driven enhancement of drought resilience.

To address these challenges, the LocAlly led Climate adapTation ChampION (ACTION) Grant Program was implemented. This program — supported by the CGIAR Climate Action Science Program and in partnership with the national Ministry of Agriculture and the Local Authority in Monze District — facilitated the installation of a solar-powered borehole in Hanzila. This initiative aimed to improve the community's access to water for drinking, domestic uses, crop production, and livestock management, thereby leaving no one behind in mitigating the effects of water scarcity.

The ACTION program employed a polycentric approach to water governance. It focused on horizontal decision-making that emphasised community-based water tenure to ensure active bottom-up participation from the community from project conception to implementation phases. Embedded in vertical polycentricity between Hanzila and the Local Authority, the project aimed to overcome siloed approaches, ensure sustainability and provide lessons for scaling up integrated locally-led interventions intended to strengthen climate resilience in other rural areas of Zambia and beyond.

The aims of this paper are to examine the horizontal and vertical polycentric decision-making processes involved in the locally-led strengthening of drought resilience — anchored in Hanzila's customary water tenure arrangements — and to assess the livelihood outcomes associated with the solar-powered borehole initiative.

2. Methods and materials

2.1. Study area

The ACTION Grant Program was implemented with Hanzila community in Southern Zambia. Located approximately 20 km west of Monze and about 300 km south of Lusaka, Hanzila is situated in a dry, arid region characterised by a sub-tropical climate [38,39]. The area experiences distinct wet and dry seasons; concentrated rainfall between November and March, followed by a prolonged dry season from April to October [38]. The region's moderate to high temperatures and erratic rainfall patterns create challenges for both water management and agriculture [38].

Most residents in Hanzila rely on subsistence farming by cultivating crops such as maize, groundnuts, beans, cotton, sunflower, soya beans, and sweet potatoes, all of which depend heavily on seasonal rainfall [42,43]. Livestock rearing of cattle, goats, sheep, and chickens is also crucial to their livelihoods [43].

2.2. Methods

This section explains the methods and timeline employed; first, to facilitate and document the integrated locally-led planning, design, construction, and use of the solar-powered borehole; and second, to subsequently assess the livelihood outcomes of the borehole.

2.2.1. Facilitation and documentation of the participatory process. In early 2023, the ACTION project team approached the Local Authority of Monze district. In 2023/2024, due to the impacts of the drought, Monze district prioritised water projects. The Local Authority recommended Hanzila for the implementation of a locally-led initiative to strengthen drought resilience. Hanzila was identified as a community with strong development aspirations hindered by limited access to water resources. Additionally, there was a high level of unity within the community, suggesting community members to be receptive to encouragement and willing to grow and advance.

The subsequent participatory process was facilitated by the first author, in collaboration with the Monze Local Authority, and implemented between February 16, 2023 and September 23, 2023. This part of the study focused on developing and establishing the new water supply system relying on the community's age-old and locally-specific integrated water tenure as well as their priorities. The communities' diagnosis of the pre-project situation also informed the baseline information against which to assess changes and outcomes in the second part of the study. The Local Authority continued its support during the planning, design and construction process, and still provides post-construction support to maintain sustainable operation.

2.2.2. Assessment of livelihood outcomes. A year later (August 12 to October 4, 2024), the first author investigated the post-construction operation and use of the solar-powered borehole, the livelihood outcomes and remnant challenges associated with the multi-purpose water supply. The study combined quantitative and qualitative data-collection methods to assess livelihood outcomes on water access and usage.

a) Quantitative data collection

A survey was conducted among 40 randomly sampled households in Hanzila, represented by 19 men and 21 women respondents. The survey employed a structured questionnaire designed to assess changes in water use patterns and their effects on livelihoods. This gender-balanced sample ensured the inclusion of diverse perspectives on how the solar-powered borehole influenced water access and use within the community.

b) Qualitative data collection

In addition to the survey, qualitative data were gathered through key informant interviews (KIIs) and focus group discussions (FGDs).

1. KIIs: Four interviews were conducted with representatives from the District Council and the Ministry of Agriculture. These interviews provided institutional perspectives on the governance, the technical aspects, and broader outcomes of the solar-powered borehole project.

2. FGDs: The first FGD involved 21 participants, including 11 men and 10 women, primarily ordinary community members. Participants were selected to represent a diverse demographic range, including age, gender, and livelihood activities, such as small-scale farming, gardening, cattle keeping, and rearing small livestock. This FGD focused on participants' experiences, water usage patterns, challenges encountered, and perceived benefits of the solar-powered borehole.

The second FGD was open to all community members of Hanzila, attracting 72 participants. This larger session aimed to gather comprehensive community-wide insights into the effects of the borehole, changes in water access, livelihood opportunities, and social dynamics.

During these interviews and discussions, participants provided oral feedback on their access to water before and after the borehole's implementation, highlighting observed changes in livelihoods and other community dynamics.

c) Ethical Considerations

The study adhered to ethical guidelines set by the Institutional Review Board (IRB) of the International Water Management Institute (IWMI). These guidelines align with IWMI's Research Ethics Policy and the CGIAR Research Ethics Code and Responsible Data Guidelines. These are grounded in the Belmont Report and comply with the rules of the US Federal Policy for the Protection of Human Subjects. IWMI's IRB approved the project with certificate number 2023/45 on November 8, 2023, recommending [oral] consent for the interviews and FGDs which was implemented by the project.

Informed consent was obtained for all KIIs and FGDs, with special consideration given to illiterate participants. The first author ensured that participants were adequately informed of the study objectives, data-collection methods and the voluntary nature of their participation. Consent was obtained orally, and participants were assured of the confidentiality and anonymity of their responses throughout the process.

d) Data analysis

The data collected from the surveys was entered into Statistical Package for Social Sciences (SPSS). Next, the data was cleaned by checking for missing or inconsistent values; these were corrected and coded as necessary. Afterwards, descriptive statistics were used to summarise the key variables of the respondents. The results were interpreted based on their statistical significance and relevance to the study objectives.

To analyse data from FGDs and KIIs, the audio recordings were transcribed verbatim, and the transcripts were reviewed for accuracy. Next, a thematic analysis was conducted by manually coding the data to identify recurring patterns, ideas, and categories related to the research objectives. Key themes were developed through an iterative process of grouping similar codes and interpreting their underlying meanings. Differences in perspectives among the various participant groups were also examined to capture a diverse range of views. The analysis aimed to draw insights that accurately reflect community experiences, challenges, and proposed solutions.

2.3. Conceptual foundations

2.3.1. Polycentric water governance. Polycentric governance is a concept coined in the 1960s, describing the different layers of management systems wherein several overlapping authorities take part in decision-making processes [44,45]. Today, the concept of polycentric governance has gained currency among many scholars and practitioners [46–49]. Scholars use polycentricity to understand and identify decision-making processes and their integration laterally within and across units. This is referred to as horizontal polycentricity and integration. When decisions are passed on from the top authority to lower levels of the governance process and vice versa, this is referred to as vertical polycentricity and integration [50].

In recent years, the concept of polycentric governance has gained prominence in the planning and management of water and land resources, including forestry [9,51]. Coordinated efforts among governments, financiers, implementers, and communities have become increasingly vital in these areas. The intricate processes of decision-making, at various levels, underline the importance of both vertical and horizontal planning in the effective management of water resources.

2.3.2. Local horizontal polycentric governance. Local horizontal polycentric governance is integrated. However, public water interventions primarily focus on developing infrastructure for domestic use, as defined by the Water, Sanitation and Health (WASH) sector. Sections within the larger agricultural sector do address smallholder irrigation schemes and water availability for livestock. Earlier, vertical engagements with communities used to be narrow, only considering the particular focus of the department's or section's mandates, ignoring other uses. Although the WASH sector tries to ensure the accessibility of public resources for all, top-down approaches can hamper such inclusivity. When such projects are built on publicly owned land, access is guaranteed for all. However, where public land is not available, there is the risk that any community member willing to let out part of their land to be used for construction may claim primary, or even exclusive, access to that water resource. This issue can be avoided if the land title holder agrees to sign over their rights to the specific portion of land, transferring those rights to the community [5]. The agricultural sector often pays less attention to leaving no-one behind.

However, in practice, there are several important nodes of local decision-making regarding access to water. For example, public infrastructure is often repurposed for multiple uses beyond the original intent of the implementing sector. In rural areas of Zambia and elsewhere, water is essential for human survival and the associated multi-faceted livelihoods [52,53]. Multi-purpose infrastructure is also cost-effective [54–56]. Furthermore, public infrastructure represents just one of the several water sources available. Communities fulfil their various water needs through a combination of resources: rainwater, aquifers and surface water sources such as open streams, rivers, and lakes [5]. Additionally, communities often develop and finance their own self-supplied infrastructure, which typically serves multiple purposes. Today, the availability of mechanised pumps and energy sources has further accelerated self-supply efforts.

Communities also collectively and horizontally decide how they choose to share natural water resources — both within their own community and, occasionally, with neighbouring communities [57]. For example, landowners whose properties/land are situated adjacent to or upstream of water sources may assert greater access to those resources. However, such claims are generally not exclusive; local rights of way allow other community members to also benefit from the water; water is considered a natural resource meant to be shared by everyone [58,59]. These collaborative, horizontal polycentric processes for managing water usage, natural resources and infrastructure — whether funded by the public or through self-supply — are a testament to extensive local knowledge and resources. They critically influence the community's priorities for making incremental improvements, especially concerning interventions to increase drought resilience that are initiated at the local level [5].

2.3.3. Vertical polycentric governance. Governments operate vertically across tiers, and communities tend to mainly engage with local authorities. In Zambia, the responsibility of enhancing access to water for rural communities lies with the Local Authority under the Ministry of Local Government and Rural Development in the Rural Water Supply and Sanitation (RWSS) unit. Most water supply-related projects are financed by the Constituency Development Fund (CDF). The CDF is a general decentralised government fund exclusively geared to local-level community development [60]. Unlike donor funds, it is a reliable and guaranteed source of funding for each district. To access these funds, communities engage with their local governance structures, including the Area and Ward Development Committees and traditional leaders. This engagement is carried out through a horizontal and vertical participatory process enabling community members to express their identified needs, concerns, and wishes for new projects related to water, agriculture, or other areas.

A selected community project committee then elevates these concerns by connecting the community's needs with the district-level government. Upon receiving these requests, district officials conduct assessments to determine the extent of these needs. They present the identified issues at district council meetings, where projects that require the most support are prioritised for funding. Due to numerous annual requests, the available funds are not always sufficient to meet all demands. As a result, unfunded projects are either suspended for the year or await external financing that can be sought to supplement government efforts. All the details for communities in need are recorded at the district level and support is awaited.

After a project is completed, the Local Authority remains responsible for ensuring that water supply systems, including boreholes, wells, dams, or other water infrastructure, remain functional. They conduct routine visits, provide training for local communities on maintaining the water infrastructure, raise awareness about safeguarding it, and establish reporting mechanisms for corrective measures in the case of breakdowns.

At district level, the Local Authority coordinates with officials, including those in charge of agriculture. This was the context of horizontal and vertical decision-making at the interface with the community in the ACTION project in Hanzila. The Local Authority not only recommended Hanzila but in fact continued to play a role during the project implementation. For example, the Authority issued a permit to the contractor for drilling the borehole after confirming that the selected site met the necessary criteria for rural water supply. It also consistently advised the community on the technical aspects of the borehole during implementation and to date, continues to provide post-construction support for sustainability. The locally-led process in Hanzila is conceptualised in Fig 1. This illustrates the typical phases in the project cycle: initiating collaboration, diagnosis, envisioning solutions, fitting the financial framework, implementation (procurement and construction), and use. Involving the community through horizontal processes from the very onset prevents top-down decision-making. It ensures that all community members are engaged — to jointly diagnose their horizontal water tenure and the challenges they face, and to propose their own integrated solutions that meet all their water needs — rather than only participating during the handover of a project once all preceding steps have been decided externally, often for only a single water use.

Fig 1. Phased participatory process to implement community-led water infrastructure to enhance resilience to health, agriculture and food security.

https://doi.org/10.1371/journal.pwat.0000356.g001

2.4. Structure

The remaining part of this paper is structured as follows: Section 3 presents the results of the polycentric decision-making processes in the phased community-led development of the solar-powered borehole; Section 4 illustrates the findings of the assessment of the livelihood outcomes associated with the intervention; Section 5 puts forth a discussion of the findings; and Section 6 presents the conclusion and lessons learned, offering recommendations for scaling-up similar initiatives in other contexts in Zambia and elsewhere.

3. Results: The locally-led decision-making processes and water governance

This section presents the results of the participatory process implemented during the development of the solar-powered borehole, including the base-line situation to compare with the outcomes, from February to September 2023, as well as the operation of the solar-powered borehole and the sharing of water thereafter.

a) Initiating Collaboration

In February 2023, the ACTION team and a Ministry of Agriculture representative visited Hanzila community to discuss the ACTION project and set goals. They explored how horizontal polycentric governance could benefit the community by enhancing water access for irrigation, drinking, domestic uses, and livestock amid the impacts of climate change. Community members confirmed their water challenges and welcomed the project, leading to the creation of a collaborative structure for sustainable solutions involving the ACTION project, the district government, and Hanzila community itself.

b) Diagnosis

This was followed by a more detailed joint diagnosis of horizontal water governance decision-making and the challenges faced by Hanzila community due to drought and water scarcity. This involved local leaders, farmers, pastoralists, the elderly, and the youth. They mapped their existing ground- and surface water sources and outlined how they served multiple uses: domestic, drinking for livestock, and irrigated vegetable gardening. The water sources included two boreholes equipped with hand pumps, deep and shallow wells, and open sources such as rivers, streams, and scoop holes. During the rainy season, people also harvested rainwater for immediate household use. The primary water source was a public borehole outfitted with a hand pump which provided clean water for drinking, domestic use, livestock, and occasionally, crop watering, particularly during the dry season. However, it served approximately 500 households, leading to congestion, long wait times, and conflicts over access. Many people walked long distances to procure water when they could not wait in line. A nearby school also had a borehole reserved for its own use, limiting access for the community.

Streams and scoop holes supplied water during the rainy season, but were prone to dry up increasingly earlier each year due to drought, leaving residents with few options. Consequently, those dependent on gardening often had to stop due to limited water availability. Men, in particular, reverted to herding their livestock to distant water sources. Others used the scoop holes for drinking and domestic uses, and a few small livestock owners returned to relying on the borehole with the hand pump. Hence, community members highlighted the inadequacy of water for drinking, livestock, and irrigation, further exacerbated by frequent breakdowns of the hand pump.

c) Envisioning solutions

Based on the participatory diagnosis and identification of challenges, separate groups of participants explored potential solutions to address their unique needs. Men were more interested in procuring water that would improve access to water for livestock drinking, such as dams, weirs, and solar-powered boreholes. Women were more keen for improving access to water for drinking and domestic uses and thereby reduce the challenges of queuing for long hours. They also proposed water access for the irrigation of small gardens. Women were more interested in having a solar-powered borehole and an additional borehole with a hand pump.

With these proposed suggestions, a series of discussions were undertaken to agree on a water source that would address all the needs of both men and women. After thorough deliberation, the community settled for a solar-powered borehole that would most likely meet the community's primary water needs, encompassing drinking, other domestic uses, irrigation, and water for livestock.

d) Fitting the financial framework

Once a solar-powered borehole was identified as the preferred water infrastructure, the ACTION project estimated the budget needed at ZWM 438,688.80 (approximately USD 17,550) for installing a 100 m deep borehole. This installation included an elevated tank stand with a storage capacity of 10,000 L. Additionally, the network of pipes would cover a radius of 1 km coupled with 10 strategically placed access taps throughout the village to ensure fair access to water for various uses.

To implement this project, a competitive bidding process was initiated to select a contractor experienced in installing solar-powered boreholes, working closely with community members.

e) Implementation

Once the contractor had been appointed, implementation started. A meeting was held with the ACTION facilitator, the contractor, and members of Hanzila community, including women, men, young people, small-scale farmers and livestock keepers, as well as community leaders. Per the meeting, it was agreed that the site should: be centrally located for easy access and security against theft; be accessible for all, without individuals claiming ownership of the borehole; and have sufficient groundwater yields. Community members proposed to have the borehole drilled on a 3 ha piece of land that the chief had awarded to all farmers within the community for their gardening activities. His signed letter confirmed community ownership of the land. Within the confines of the 3 ha, the site chosen for the borehole was only 100 m away from homesteads, to enable regular monitoring of the borehole and prevent vandalism and theft of the borehole parts. The geophysical surveys conducted by the contractor confirmed the presence of sufficient yield at the site.

The actual implementation of the water infrastructure began in July 2023 following the contractor's acquisition of a construction permit. This borehole was constructed with a 10,000 L water tank, a supply network extending to 1 km radius, and 10 garden taps placed strategically within the community. Throughout this process, community members monitored the contractor's work to ensure that the borehole installation aligned with the project requirements and to address any issues that arose. In Fig 2, we show the implemented borehole in relation to water access points for drinking and productive uses.

f) Using the water resource

Following the installation of the borehole, there was an official handover ceremony in September 2023, after which community members began using the new facility.

The FGDs and KIIs conducted in Hanzila community revealed that, by August 2024, the water users, with the help of water committee members, had established norms to ensure that water resources were shared fairly, with prioritisation for primary water needs.

Community members had agreed to implement a rotational system for accessing water for drinking, domestic uses, crop irrigation, and livestock watering. All domestic users could access water at any time of the day, as long as there was water in the tanks and flowing through the supply lines. However, community members were encouraged to access water for drinking and other domestic needs from morning until noon.

Different schedules were in place for accessing water for irrigation and livestock drinking. Livestock watering was allocated a window of two hours from noon until 2 pm. For the 3 ha of communal land used for gardening, a different approach was applied. The gardens were divided into sections, each of which was assigned a specific time for watering of the crops. For

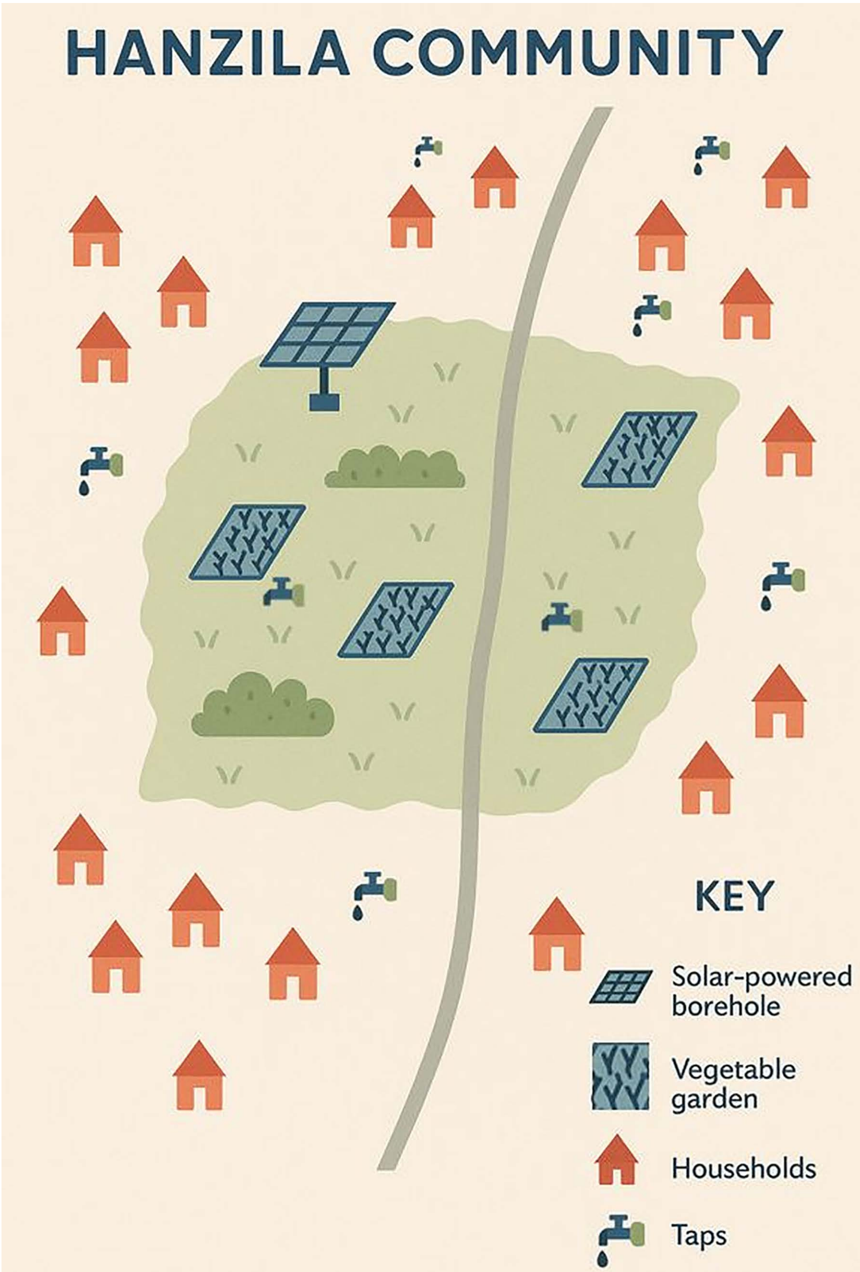


Fig 2. Map of Hanzila community showing the location of households in relation to water access points for drinking and productive uses.

https://doi.org/10.1371/journal.pwat.0000356.g002

example, if the first section watered their crops on a given day, they could not water again the next day to allow another section to access water for their crops. On the third day, the schedule returned to the first section for watering. This rotation was designed to prevent overworking the borehole pump and to ensure sufficient water for all necessary uses in the tank each day.

Additionally, crop irrigation was scheduled for the late afternoon. This arrangement was designed to prevent inconveniencing the individuals needing water for drinking and domestic uses. Late afternoon watering also helped retain soil moisture for proper crop growth, as opposed to wasting water through evaporation during the heat of the day.

These established rules of access served two main purposes: first, they allowed for the needs of various users to be met and different priorities within the community to be addressed; and second, they prevented overburdening the solar-powered borehole, which could be a considerable challenge if users were allowed unfettered access to water without guidance.

In addition to protecting the borehole's operation, these normative rules promote community cooperation and unity. The community collaborates and takes collective responsibility for managing water resources, ensuring the sustainability of the solar-powered borehole.

The second part of the study follows below: the assessment of the outcomes of the project for people's livelihoods and drought resilience, including the remaining challenges after one year of operation of the solar-powered borehole.

4. Results: Livelihood outcomes

4.1. Outcomes of the solar-powered borehole on domestic water access and uses

This section assesses the outcomes of the new solar-powered borehole on water availability for drinking and household uses, while identifying persistent challenges of access such as distance, equity, or technical constraints. The results show changes that the survey respondents noted before and after the implementation of the borehole.

The installation of the solar-powered borehole in Hanzila has significantly enhanced access to clean and convenient water sources for drinking and domestic uses, addressing various challenges faced by the community. Before the borehole was installed, 67.5% of survey respondents relied on the public borehole with a hand pump, 20.0% used open sources such as streams and scoop holes, while 13.0% accessed water from deep or shallow wells.

After the solar-powered borehole became operational, 85.0% of respondents began using it, benefiting from taps installed closer to their homes. This transition eliminated reliance on open sources and significantly reduced the number of people using wells (10.0%) or the public hand-pump borehole (5.0%), and notably, with no reports of queuing (See Fig 3).

A chi-square test was conducted to assess changes in the use of various water sources, and the results indicated a highly significant effect ($\chi^2(3, N=40) = 64.0$, $p<0.001$). A follow-up analysis using two-proportion z-tests revealed noteworthy changes in specific water source usage. There was a substantial increase in the use of the solar-powered borehole from 0.0% (95% Confidence Interval (CI): 0.0–8.8) before its implementation to 85.5% (95% CI: 70.9–92.9) after the installation ($z=5.20$, $p<0.001$), while the use of the borehole with a hand pump decreased significantly from 67.5% (95% CI: 52.5–79.1) to 5.0% (95% CI: 1.6–14.4) ($z=3.08$, p 0.002). Additionally, reliance on open water sources experienced a total elimination from 20.0% (95% CI: 10.2–35.0) to 0.0% (95% CI: 0–9) ($z=3.65$, $p =< 0.001$) (S1 Table).

The results of the chi-square test indicate a significant shift in the utilisation of various water sources, emphasising the effectiveness of developing a solar-powered borehole aimed at improving water accessibility in Hanzila community. The borehole has enhanced the reliability of the water supply and importantly, reduced dependence on traditional, less sustainable methods (such as open sources) for drinking and domestic use.

Furthermore, the implementation of a solar-powered borehole resulted in a significant reduction in the distance required to access water. Before its implementation, 62.5% of respondents reported having to travel over 500 m to fetch water. In a stark contrast, the percentage dropped to 15.0% after the borehole was installed (Fig 4). This improved proximity not only reduced physical effort but also freed up time for other productive activities. This shift highlights the transformative impact of the borehole on water accessibility as well as overall community resilience.

Moreover, before the solar-powered borehole's implementation, no household had direct access to water running through to their households, and none reported obtaining water from a location less than 50 m away. Following the borehole's implementation, 20.0% of respondents disclosed that they now had water available within their homes, while an additional 10.0% could access water from a tap located less than 50 m away.

To assess the statistical significance of changes in proximity to the water sources before and after the implementation of the solar-powered borehole, both McNemar's test and a chi-square test of independence were employed. McNemar's

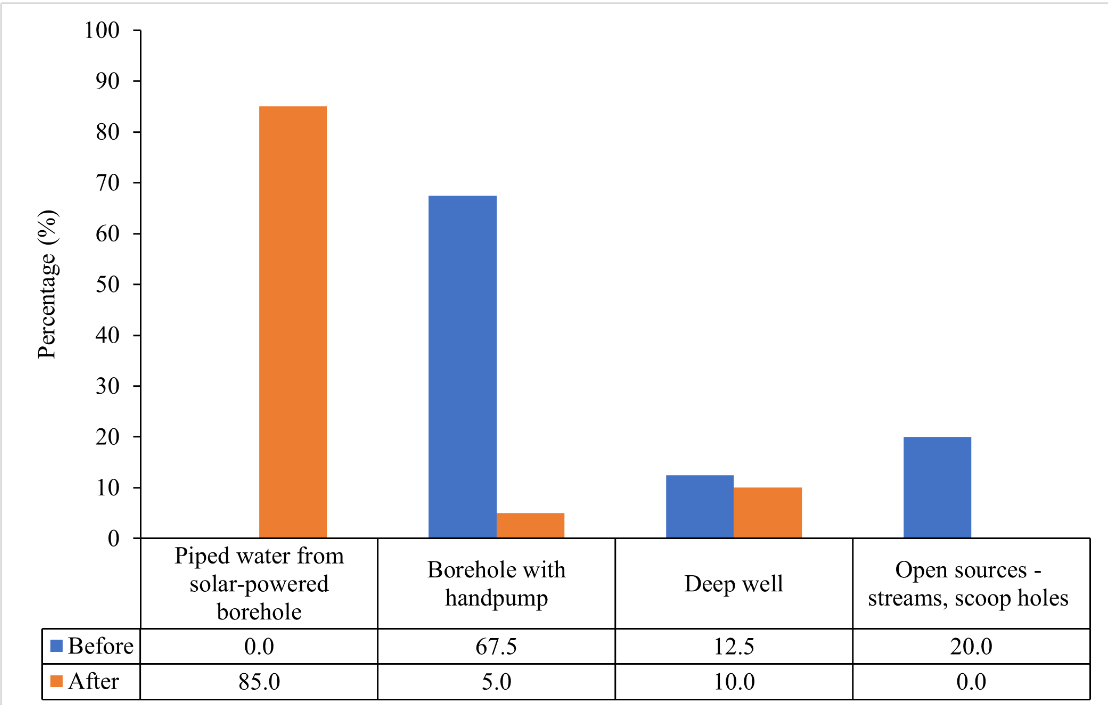


Fig 3. Sources of water for drinking and domestic use before and after the installation of the solar-powered borehole (N = 40).

https://doi.org/10.1371/journal.pwat.0000356.g003

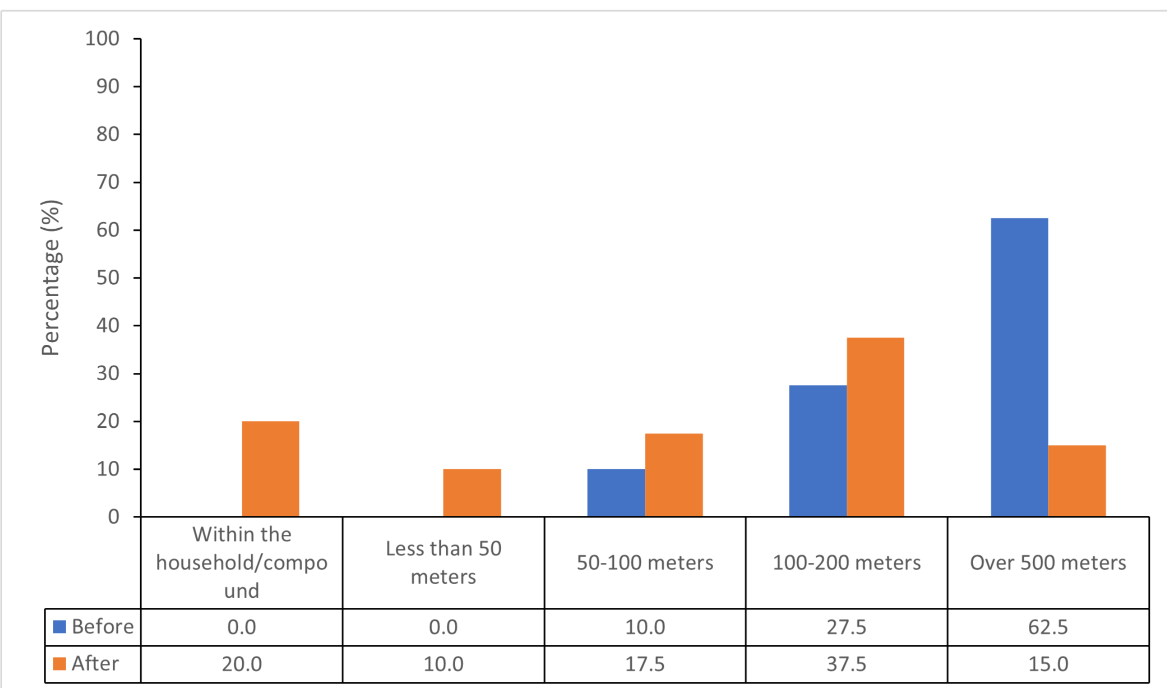


Fig 4. Distance to sources of water for drinking and domestic use before and after the installation of the solar-powered borehole (N = 40).

https://doi.org/10.1371/journal.pwat.0000356.g004

test, utilising a dichotomised measure of water access distance (≤200 meters vs. > 200 meters), revealed a highly significant improvement in accessibility following the installation of the borehole. Before its implementation, only 15 households (37.5%, 95% CI: 24.9–52.1) had access to water within 200 m; this figure increased to 35 households (87.5%, 95% CI: 73.9–94.5) after the intervention. Notably, of the 25 households (62.5%, 95% CI: 47.9–75.1) that initially depended on water sources located more than 500 m away, 20 (50.0%, 95% CI: 35.2–64.8) shifted to sources within 200 m, including 8 (20.0%, 95% CI: 10.2–35.0) that reported water availability within their household. This change was statistically significant ($p < 0.001$) (S2 Table).

The category-specific results further explain the nature of these shifts, as detailed in S2 Table. We observed statistically significant improvements in access to water within the household (0.0% before vs. 20.0% after, $z = 2.96$, $p < 0.01$) and at less than 50 m (0.0% before vs. 10.0% after, $z = 2.00$, $p < 0.05$). The percentage of households travelling more than 500 m declined dramatically from 62.5% (95% CI: 48–76) to 15.0% (95% CI: 6–27), representing the largest and most significant shift ($z = -4.78$, $p < 0.001$).

In contrast, changes observed at intermediate distances (50–100 m: 10.0% to 17.5%; 100–200 meters: 27.5% to 37.5%) did not reach statistical significance ($p = 0.246$ and $p = 0.400$, respectively). The most pronounced improvement was the reduction in households travelling more than 500 m, which fell sharply from 62.5% (95% CI: 47.9–75.1) to 15.0% (95% CI: 6.0–27.3), representing a highly significant decrease ($z = –4.78$, $p < 0.001$).

Complementing these results, a chi-square test comparing the full distribution of water access categories before and after the intervention indicated a highly significant change, $\chi^2(4, N = 40) = 27.8$, $p < 0.001$. Collectively, these findings demonstrate that the intervention substantially reduced reliance on distant water sources while significantly increasing the number of households with water access within or very near their homes.

The results also indicate significant time-saving in Hanzila village. Long queues and extensive waiting times previously faced by women and children in fetching the water have now been reduced. While 55.0% of the interviewed households reported that it took over an hour to wait in line for water for drinking and domestic uses before the intervention, currently, no households take more than an hour to access water from the solar-powered borehole (Fig 5).

Results reported in Fig 5 were also brought forth during an FGD, indicating that the implementation of the borehole and strategic installation of the taps has drastically reduced the time and effort previously spent waiting at the single clean water source in the village:

> "…nowadays, we have plenty of time to focus on other tasks like cooking and even find time to relax and spend with family. We no longer worry about searching for water or enduring long queues to fill just one or two containers that wouldn't suffice for all our household needs. Within minutes, we can fill all the containers in our home with water for drinking, cleaning dishes and washing clothes. This allows us ample time to clean our homes and dishes promptly." — Female respondent in an FGD in Hanzila village.

This convenience has not only eliminated the need for long waiting periods, but also allowed women to dedicate more time to their families and household chores without the fatigue of fetching water from overcrowded sources.

The implementation of the solar-powered borehole has led to positive outcomes for domestic water use; however, there are persisting challenges. One such obstacle is unequal access to water within the community. The project established supply lines covering a radius of one km. Unfortunately, community members living farther away from the installed supply lines and access taps — particularly on the southern side of the village — have not been able to fully benefit from these improvements. Even after the intervention, they must still travel long distances to fetch water for drinking and domestic uses.

Community members with the necessary financial means have taken it upon themselves to extend the supply lines to their homes or closer to their homesteads. In contrast, those who cannot afford to pay for these extensions continue to have to transport water over long distances from the taps located within a 1 km radius.

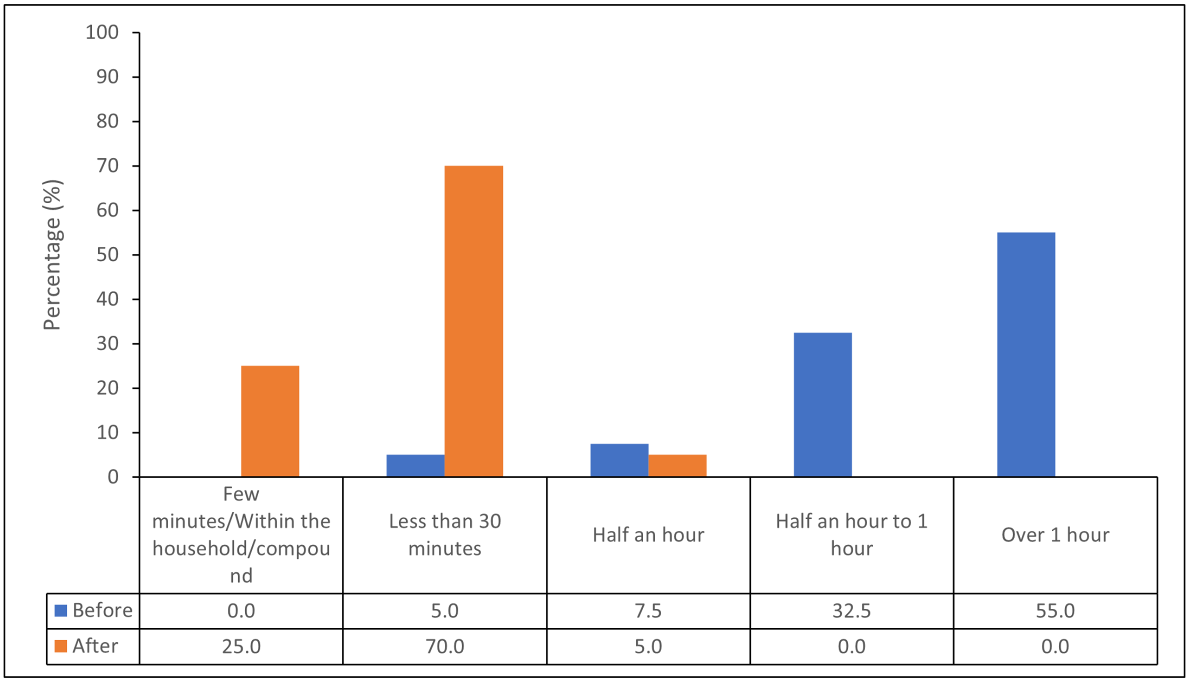


Fig 5. Time spent to access water for drinking and domestic uses before and after implementation of the solar-powered borehole in Hanzila village (N = 40).

https://doi.org/10.1371/journal.pwat.0000356.g005

Moreover, these households have reverted to using unclean water sources, such as shallow dug wells. Some families still rely on accessing hand pumps in neighbouring villages, where they encounter long queues and long waiting times.

To address the issue of unequal access, it is essential to consider this challenge during the design phase and the establishment of contributions to the construction, or tariffs, during its operation. Such higher contributions by the beneficiaries closer to the taps could help finance extensions for the poorer households who live farther away from the externally funded water supply network.

4.2. Outcomes of the solar-powered borehole for agriculture: opportunities and constraints

This section explores the role of boreholes in supporting irrigated gardening, including their contribution to enhancing productivity and food security. However, it also addresses the challenges associated with water allocation, the need for effective infrastructure for in-field water application, and the environmental constraints that necessitate consideration.

The solar-powered borehole has created new opportunities for people to grow crops during the dry season, when rain is scarce or absent. Before the borehole was implemented, dry-season irrigation options were very limited. The survey found that 77.5% of the respondents (31/40) did not have a garden prior to the intervention, with only 22.5% (9/40; 95% CI:12.3-37.5) being able to maintain a garden. After the borehole operationalised, garden ownership increased significantly to 70.0% (95% CI: 54.6–81.9), with only 30.0% (95% CI: 18.1–45.4) reporting having no garden for growing crops in the dry season (See S3 Table).

Both the chi-square test ($\chi^2(1, N = 40) = 15.8$, $p < 0.001$) and McNemar's test ($z = 3.97$, $p < 0.001$) confirmed that this increase was highly statistically significant, indicating that improved water availability strongly facilitated dry-season gardening (See S3 Table).

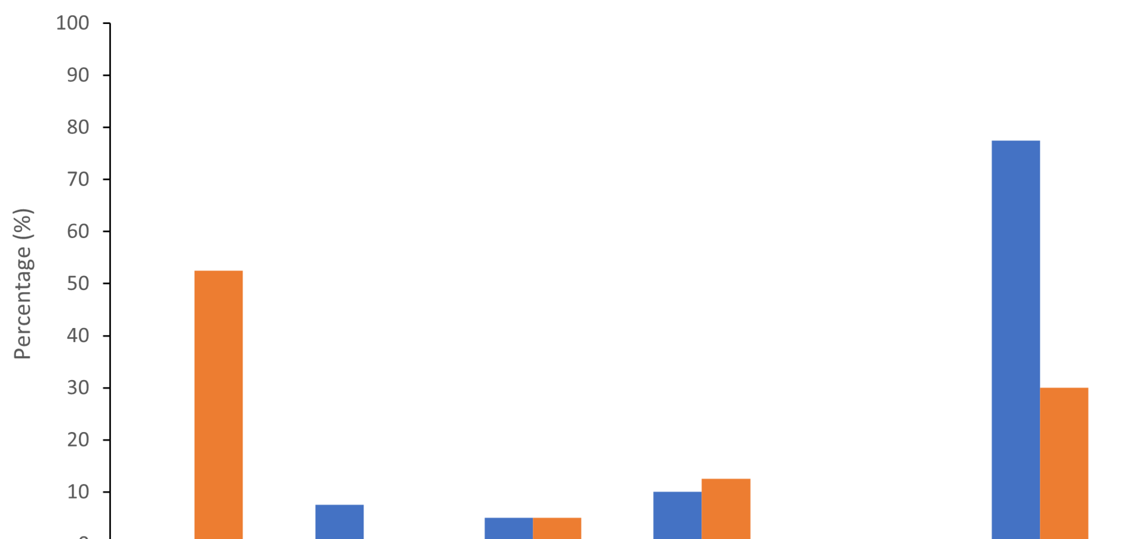
The survey results also indicate that water from the solar-powered borehole is the main enabler to start gardening. Of the respondents, 52.5% indicated that they use water from the solar-powered borehole to irrigate their crops. In contrast, only 12.5% reported using open water sources such as streams, weirs, and scoop holes. Only 5.0% relied on shallow and deep wells.

Before the solar-powered borehole was introduced in Hanzila community, only a small number of households (10.0%) used open water sources (streams, weirs, and scoop holes) for their gardens. Additionally, 7.5% of the households used a public borehole equipped with a hand pump, and 5.0% continued to use shallow and deep wells (Fig 6).

The solar-powered borehole has significantly reduced farmer reliance on unpredictable seasonal rainfall, with 70.0% of respondents who cultivate gardens indicating this benefit. They expressed confidence in their ability to continue growing crops even during drought conditions. The survey revealed that 15.0% of the respondents use their irrigated crops solely for personal consumption. Meanwhile, 55.0% of the 70.0% of gardeners reported earning an income from the sale of vegetables grown in their gardens. This indicates that the use of the solar-powered borehole has not only improved food security and nutrition but has also positively impacted household incomes (S4 Table).

During the FGDs, participants expressed how the previous season's drought had placed the community in a dire situation. Now, however, the reliable water supply from the solar-powered borehole enabled year-round irrigation for vegetables, which would not have been possible without the borehole.

"…With the drought that we experienced this last season, we are not in a terrible place anymore because we now have a reliable source of water that has allowed us to continue farming activities within this community. This could not have



	Piped water from solar-powered borehole	Borehole with handpump	Deep well	Open sources - streams, weirs, dams, scoop holes	Rain harvesting	N/A - Do not own a garden
Before	0.0	7.5	5.0	10.0	0.0	77.5
After	52.5	0.0	5.0	12.5	0.0	30.0

Fig 6. Sources of water for irrigation purposes before and after the installation of the solar-powered borehole (N = 40).

https://doi.org/10.1371/journal.pwat.0000356.g006

> been possible without the solar-powered borehole, and we would continue suffering like the rest of the people in this part of the country" — Male respondent in an FGD in Hanzila village.

Challenges related to access to water for irrigated farming are largely twofold. More than half (40.0% of respondents, with 70.0% of respondents owning gardens) indicated that they lacked pipes to facilitate irrigation. Lack of access to pipes forced farmers who were located farther from the taps to carry water in handheld buckets. This method is labour-intensive and limits the distance they can cover.

Second, 40.0% reported not having equipment for in-field irrigation, such as drip systems and sprinklers (S5 Table).

4.3. Outcomes of the solar-powered borehole for livestock watering: benefits and barriers

This section analyses the benefits of the solar-powered borehole in providing water for livestock, as well as the challenges of water competition, seasonal variation, and access.

The survey assessed the percentage of respondents who owned cattle before and after the solar-powered borehole's implementation, as well as how water was utilised for cattle drinking. Before and after the intervention, 52.5% of the respondents reported that they owned cattle. In terms of small livestock ownership (such as goats, sheep, and chickens), 92.5% of the respondents indicated that they owned at least one type of small livestock both before and after the borehole was installed.

Before the solar-powered borehole was implemented, most cattle owners relied on open water sources for their cattle's drinking needs during the rainy season. Among the respondents, 47.5% utilised these sources, while 5.0% disclosed using water from wells for their livestock. This was in a group of 52.5% of respondents who owned cattle. During the dry season, when many open sources dried up, cattle owners used to be forced to travel longer distances in search of sources that had not dried up, such as streams, weirs, or scoop holes.

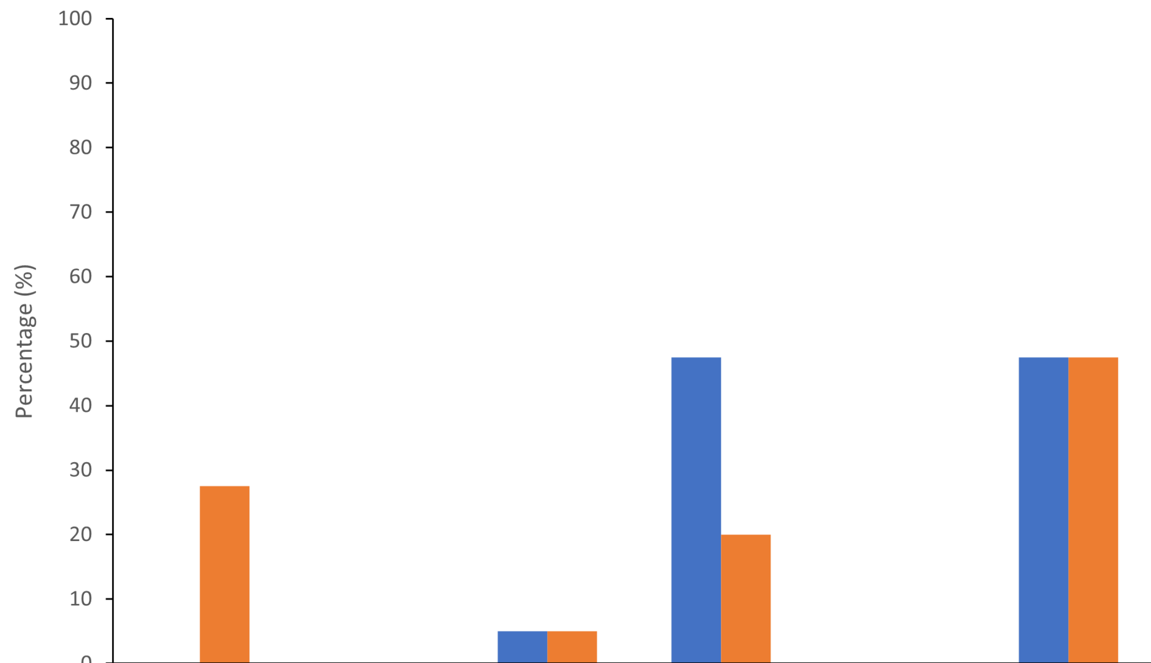
After the borehole installation, survey findings revealed significant changes in water access for cattle during the rainy and dry seasons: 27.5% of the cattle owners relied on the solar-powered borehole as their main dry-season water source, instead of open sources (Fig 7). This nearby water source alleviated the stress of having to travel long distances, while also reducing the pressure on the open resources still under use. This was also confirmed through an FGD:

> "… our routine for livestock watering has changed. We no longer need to move the cattle to distant streams to have water for drinking. We now just use hosepipes connected to the taps and put water in large basins where all our animals can get the water they need to drink water" — Male respondent in an FGD in Hanzila village.

To assess the statistical significance of changes in water use practices following the installation of the solar-powered borehole, we employed McNemar's test on paired responses from cattle-owning households.

Among the 21 households that owned cattle, reliance on open water sources was predominant before the borehole installation: 76.2% (95% CI: 54.9–89.4) used streams, scoop holes, or weirs. After installation of the solar-powered borehole, this declined significantly to 52.4% (95% CI: 32.4–71.7), as 47.6% (95% CI: 28.3–67.6) of households switched to using the solar-powered borehole for watering their cattle. Use of wells (4.8% before vs. 0% after) did not show a statistically significant change. McNemar's test confirmed that the observed shift from open sources to the solar-powered borehole was statistically significant ($\chi^2(1, N=21) = 6.12$, $p=0.013$), highlighting the borehole's critical role in improving cattle water use, especially during the dry season (S6 Table).

Regarding water for small livestock such as goats, sheep and chickens, the study revealed that nearly all respondents provided water in basins throughout the rainy and dry seasons. Specifically, 90.0% of respondents reported using piped water from a solar-powered borehole to fill the basins, while only 4% drew water for their small livestock from wells (Fig 8).



	Piped water from solar-powered borehole	Borehore with handpump	Deep well	Open sources - streams, weirs, dams, scoop holes	Rain harvesting	N/A - Do not own cattle
Before	0.0	0.0	5.0	47.5	0.0	47.5
After	27.5	0.0	5.0	20.0	0.0	47.5

Fig 7. Sources of water used for drinking for cattle during the rainy and dry season (N = 40).

https://doi.org/10.1371/journal.pwat.0000356.g007

The main challenge in accessing water from the solar-powered borehole for cattle watering is the lack of conveyance and troughs to hold water, an issue reported by 32.5% of the respondents. During the survey, cattle owners resorted to improvising water collection methods by using basins to gather water. This approach is quite tedious, since livestock require significant amounts of drinking water, estimated at 30–80 L per day per animal. Providing those quantities of water for hundreds of animals without troughs and conveyance systems is thus extremely challenging.

Other cited challenges include inadequate time allocated for providing water to the cattle and inadequate solar energy available to run the pump (S7 Table).

5. Discussion

The Hanzila solar-powered borehole project highlights the transformative potential of community participation and integrated planning in addressing increasing water scarcity in rural areas. Participatory processes — in which community members are involved from the onset of water infrastructure projects — ensure that the infrastructure meets local contexts, needs and expectations, thereby minimising implementation and post-construction challenges. This aligns with studies in Kenya [61] and Ethiopia [62] which show that engaging communities and integrating local knowledge about the complexities of conjunctive water resource management can enhance the sustainable outcomes of water projects. Instead of top-down technical designs, direct exploration of local contexts allows engineers and contractors to better align infrastructure designs with the specific location, as well as unique community priorities.

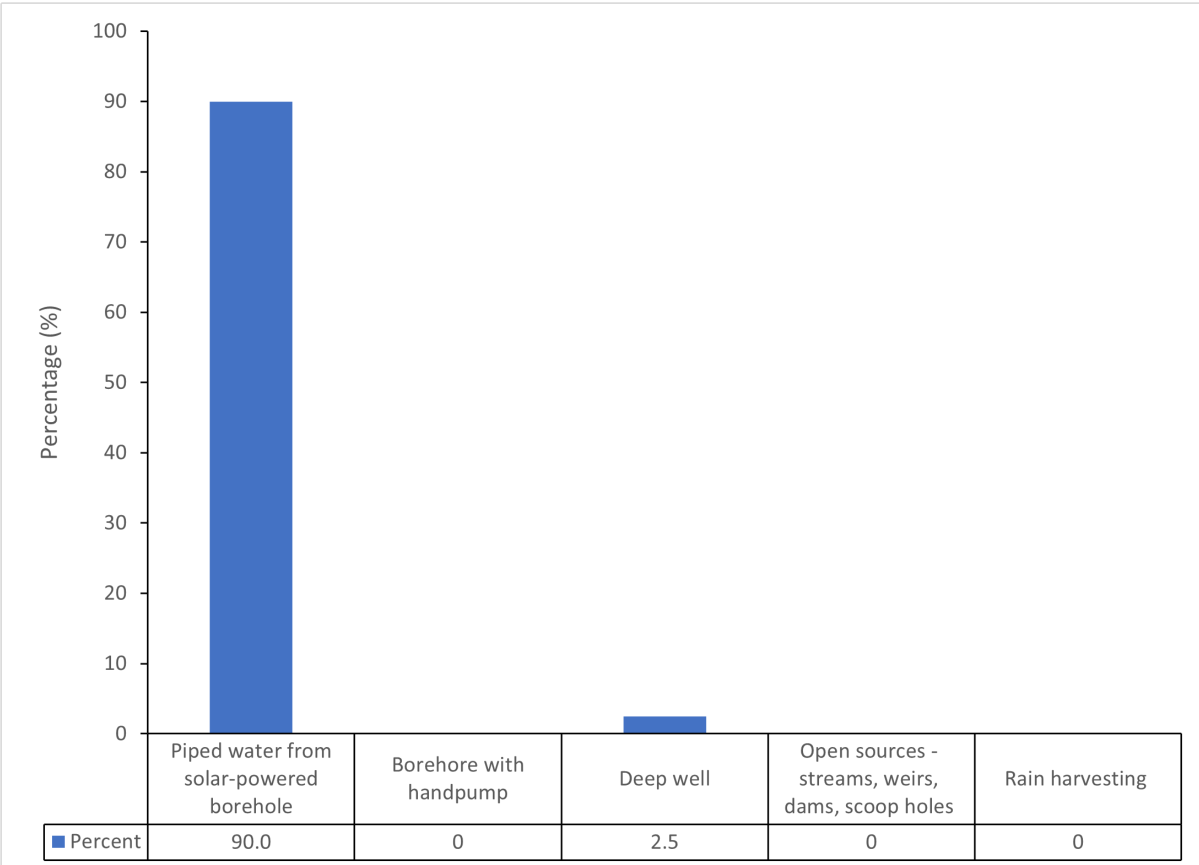


Fig 8. Sources of water used for drinking for small livestock during the rainy and dry season (N = 40).

https://doi.org/10.1371/journal.pwat.0000356.g008

The Hanzila project demonstrates the importance of acknowledging the multiple uses of water in rural settings. Water infrastructure can often serve not only domestic purposes but can also address irrigation and livestock needs. Normative rules established by the community to govern water usage are crucial in maintaining harmony and equitable access. These agreements ensure effective utilisation of water resources for multiple uses without conflict. This approach could serve as a model for similar water projects in other rural contexts. However, many government departments and development agencies still operate in silos, missing out on opportunities for horizontal and vertical cross-sector collaboration. Integrated planning, as demonstrated in Hanzila where the Local Authority and the Ministry of Agriculture worked in tandem, has the potential to become a standard practice.

One notable outcome in Hanzila has been the improved access to clean water for drinking and domestic uses, reducing reliance on unclean sources like streams and scoop holes. This intervention also supports drinking water for livestock and irrigation, and boosts nutrition and economic activities such as gardening, even during times of severe droughts. Nevertheless, some households continue to face inequities in water access due to their financial limitations, which prevent them from engaging in the extension of supply lines. Addressing this disparity requires community-driven contributions or additional support from the relevant local authorities.

The integration of external support, such as the ACTION project, into local governance frameworks enhances the sustainability of the solar-powered borehole in the long term. While government funds, such as the Constituency Development Fund (CDF), play a critical role in rural water supply, external resources can provide necessary supplementation. A polycentric governance model that incorporates horizontal community-driven processes, along with vertical support coordinated among external agencies, has proven instrumental in ensuring the long-term functionality of water infrastructure.

6. Conclusions

In conclusion, the evidence of the locally-led processes and livelihood outcomes of the Hanzila solar-powered borehole project illustrates the potential for replicating and upscaling community-led initiatives to harness their transformative power in the face of worsening water scarcity. In the broader context of polycentric water governance in Zambia and the Global South, solutions rooted in the active participation of local communities not only ensure the alignment of the infrastructure developed with the specific local resource context, needs, and priorities of the community members, but also facilitate sustainable ownership. Community-driven rules for water usage and sharing not only encourage equity but also nurtures a sense of collective responsibility, serving as a blueprint for similar projects in other rural contexts.

The Hanzila project offers a replicable governance model that merges community engagement with coordinated external assistance, essential for the sustained success of water infrastructure projects. Integrating external support within local governance frameworks is paramount for ensuring the longevity and sustainability of such initiatives.

As highlighted, the holistic approach that stimulates horizontal and vertical collaboration across government departments and other national and international development agencies opens the possibility of recognising and supporting the multifaceted uses of water. Multi-purpose infrastructure prevents redundancy and promotes comprehensive, integrated solutions, ultimately maximising the benefits of rural water infrastructure.

At the same time, lessons drawn from Hanzila also highlight the continued necessity for inclusive participation strategies that effectively navigate logistical, technical and financial obstacles to allow all voices to be heard and represented. Addressing inequities in water access — particularly for the most vulnerable households — continues to call for innovative solutions, including local contributions and support mechanisms from government authorities.

As the world faces intensifying challenges related to climate change and resource scarcity, the Hanzila solar-powered borehole project stands as an evidence-based demonstration of the effectiveness of replicable community-driven drought resilience and climate adaptation. It serves as a reminder that with strategic collaboration, tailored engagement, and a commitment to equity, resilient systems that not only address immediate water needs but also enhance livelihoods and strengthen communities against future challenges can be created. This approach not only represents a pathway to sustainable water management but also symbolises the essence of collective action required to confront the complex global challenges prevalent today.

Supporting information

S1 Table. Changes in primary water source use before and after the installation of the solar-powered borehole (N = 40).
(DOCX)

S2 Table. Changes in distance to water source before and after installation of the solar-powered borehole (N = 40).
(DOCX)

S3 Table. Household garden ownership before and after solar-powered borehole installation (N = 40).
(DOCX)

S4 Table. Perceived benefits of using the solar-powered borehole for vegetable growing (N = 40).
(DOCX)

S5 Table. Challenges of accessing water for enhanced agricultural activities from the solar-powered borehole (N = 40).
(DOCX)

S6 Table. Changes in main source of water for cattle before and after the implementation of the solar-powered borehole Installation (N = 21 cattle-owning households).
(DOCX)

S7 Table. Challenges of accessing water for drinking for cattle from the solar-powered borehole (N = 40).
(DOCX)

Acknowledgments

This work was part of the CGIAR Climate Action Science Program. We would like to thank all those who contributed to the research and supported the initiative through the CGIAR Trust Fund.

Author contributions

Conceptualization: Carol Emma Mweemba, Barbara van Koppen, Giriraj Amarnath.

Data curation: Carol Emma Mweemba.

Formal analysis: Carol Emma Mweemba.

Funding acquisition: Giriraj Amarnath.

Investigation: Carol Emma Mweemba.

Methodology: Carol Emma Mweemba, Barbara van Koppen.

Project administration: Carol Emma Mweemba.

Resources: Giriraj Amarnath.

Supervision: Barbara van Koppen, Giriraj Amarnath.

Writing – original draft: Carol Emma Mweemba.

Writing – review & editing: Barbara van Koppen, Giriraj Amarnath.

References

1. Caretta MA, Mukherji A, Arfanuzzaman M, Betts RA, Gelfan A, Hirabayashi Y, et al. Water. In: Pörtner HO, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, Alegría A, et al., editors. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press; 2022. p. 551–712.
2. IPCC. Sections. In: Lee H, Romero J, editors. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate. Geneva, Switzerland: IPCC; 2023. p. 35–115.
3. WHO. Drought in Southern Africa: Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, Zambia, Zimbabwe, Public Health Situation Analysis (PHSA) (14 October 2024). 2024. p. 1–36. Available from: https://reliefweb.int/node/4101442
4. Pahl-Wostl C. The implications of complexity for integrated resources management. Environ Model Softw. 2007;22(5):561–9. https://doi.org/10.1016/j.envsoft.2005.12.024
5. Mweemba EC, Van Koppen B, Amarnath G. Polycentrism: A case study on water access and management in community-based water tenure in Makopa and Simukale villages. Colombo, Sri Lanka: International Water Management Institute (IWMI), CGIAR Initiative on Climate Resilience. 2023. Available from: https://hdl.handle.net/10568/127727
6. Shammin MR, Haque AKE, Faisal IM. A framework for climate resilient community-Based adaptation. In: Haque AKE, Mukhopadhyay P, Nepal M, Shammin MR, editors. Climate Change and Community Resilience. Singapore: Springer; 2023.
7. Blench R. You can't go home again: Pastoralism in the twenty-first century. Int J Agric Sustain. 2001;3(1):4–11.

8. Nelson DR, Adger WN, Brown K. Adaptation to Environmental Change: Contributions of a Resilience Framework. Annu Rev Environ Resour. 2007;32(1):395–419. https://doi.org/10.1146/annurev.energy.32.051807.090348
9. Muller M. Polycentric governance: water management in South Africa. Manag Procure Law. 2012;165(3):193–200. https://doi.org/10.1680/mpal.11.00018
10. van Koppen B. Living customary water tenure in rights-based water resource management in sub-Saharan Africa. IWMI Research Report 183. Colombo, Sri Lanka: International Water Management Institute; 2022. 41 p.
11. FAO. Unpacking water tenure for improved food security and sustainable development. Land and Water Discussion Papers. Rome, Italy: Food and Agriculture Organization; 2020. 40 p.
12. Troell J, Keene S. Legal recognition of customary water tenure in Sub-Saharan Africa: unpacking the land-water nexus. IWMI Research Report 182. Colombo, Sri Lanka: International Water Management Institute; 2022. 33 p.
13. Samaddar S, Oteng-Ababio M, Dayour F, Ayaribila A, Obeng FK, Ziem R, et al. Successful Community Participation in Climate Change Adaptation Programs: on Whose Terms?. Environ Manage. 2021;67(4):747–62. https://doi.org/10.1007/s00267-020-01421-2 PMID: 33462680
14. Moser CO, Satterthwaite D. Towards pro-poor adaptation to climate change in the urban centres of low- and middle-income countries. Environ Urban. 2008;20(1):1–18.
15. Moriarty P, Smits S, Butterworth J, Franceys R. Trends in rural water supply: towards a service delivery approach. Water Altern. 2013;6(3):329–49.
16. Biermann F, Boas I. Preparing for a Warmer World: Towards a Global Governance System to Protect Climate Refugees. Global Environmental Politics. 2010;10(1):60–88. https://doi.org/10.1162/glep.2010.10.1.60
17. Venner K, García-Lamarca M, Olazabal M. The Multi-Scalar Inequities of Climate Adaptation Finance: A Critical Review. Curr Clim Change Rep. 2024;10(3):46–59. https://doi.org/10.1007/s40641-024-00195-7
18. Mfitumukiza D, Roy AS, Simane B, Hammill A, Rahman MF, Huq S. Scaling local and community-based adaptation. Global Commission on Adaptation Background Paper. Rotterdam and Washington, DC: Global Center on Adaptation. 2020. Available from: https://www.gca.org/global-commission-on-adaptation/report/papers
19. Ostrom E. Polycentric systems for coping with collective action and global environmental change. Glob Environ Change. 2010;20(4):550–7. https://doi.org/10.1016/j.gloenvcha.2010.07.004
20. Huitema D, Mostert E, Egas W, Moellenkamp S, Pahl-Wostl C, Yalcin R. Adaptive Water Governance: Assessing the Institutional Prescriptions of Adaptive (Co-)Management from a Governance Perspective and Defining a Research Agenda. Ecol Soc. 2009;14(1). https://doi.org/10.5751/es-02827-140126
21. Jian C. Innovative financing mechanisms for climate action: Unlocking capital for a sustainable future. 2025. https://doi.org/10.1007/978-981-96-7975-1_13
22. Bose S. Adaptation finance: A review of financial instruments to facilitate climate resilience. In: Brears RC, editor. The Palgrave Handbook of Climate Resilient Societies. Cham: Palgrave Macmillan; 2021.
23. Kalantary C. Climate Change in Zambia: Impacts and Adaptation. Glob Majority E-J. 2010;1(2):85–96.
24. IAPRI. Zambia Agriculture Status Report 2021. Lusaka, Zambia: Indaba Agricultural Policy Research Institute. 2021. Available from: https://www.iapri.org.zm/download/agriculture-status-reports-2021/
25. OCHA. Zambia: Drought Response Appeal May 2024 - December 2024 (May 2024). United Nations Office for the Coordination of Humanitarian Affairs. 2024. Available from: https://www.unocha.org/publications/report/zambia/zambia-drought-response-appeal-may-2024-december-2024-may-2024
26. Armitage DR, Plummer R, Berkes F, Arthur RI, Charles AT, Davidson-Hunt IJ, et al. Adaptive co-management for social–ecological complexity. Front Ecol Environ. 2008;7(2):95–102. https://doi.org/10.1890/070089
27. Lemos MC, Agrawal A. Environmental Governance. Annu Rev Environ Resour. 2006;31(1):297–325. https://doi.org/10.1146/annurev.energy.31.042605.135621
28. Kaiser C. Rethinking polycentricity: on the North–South imbalances in transnational climate change governance. Int Environ Agreements. 2022;22(4):693–713. https://doi.org/10.1007/s10784-022-09579-2
29. Jain S. An empirical economic assessment of impacts of climate change on agriculture in Zambia. Policy Research Working Paper 4291. Washington, DC: World Bank. 2007. Available from: https://openknowledge.worldbank.org/server/api/core/bitstreams/14a2bc43-e1f3-50b4-a668-11ffff352368/content
30. Neubert S, Kömm M, Krumsiek A, Schulte A, Tatge N, Zeppenfeld L. Agricultural development in a changing climate in Zambia. Studies Paper No. 57. Bonn, Germany: German Development Institute. 2011. Available from: https://www.files.ethz.ch/isn/128010/Studies%2057.pdf
31. Ostrom E. Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge, UK: Cambridge University Press; 1990.
32. Berkes F, Folke C. Linking social and ecological systems: Management practices and social mechanisms for building resilience. Cambridge, UK: Cambridge University Press; 1998.
33. Dietz T, Ostrom E, Stern PC. The struggle to govern the commons. Science. 2003;302(5652):1907–12. https://doi.org/10.1126/science.1091015 PMID: 14671286

34. Agrawal A. Common Property Institutions and Sustainable Governance of Resources. World Dev. 2001;29(10):1649–72. https://doi.org/10.1016/s0305-750x(01)00063-8
35. Amarnath G, Mweemba C, Manishimwe E, van Koppen B. Locally led climate action for sustainable community resilience. Colombo, Sri Lanka: International Water Management Institute, CGIAR Initiative on Climate Resilience. 2023. 8 p. Available from: https://hdl.handle.net/10568/132251
36. Lebu S, Lee A, Salzberg A, Bauza V. Adaptive strategies to enhance water security and resilience in low- and middle-income countries: A critical review. Sci Total Environ. 2024;925:171520. https://doi.org/10.1016/j.scitotenv.2024.171520 PMID: 38460697
37. Green PA, Vörösmarty CJ, Koehler DA, Brown C, Rex W, Rodriguez Osuna V, et al. Mapping a sustainable water future: Private sector opportunities for global water security and resilience. Glob Environ Change. 2024;88:102906. https://doi.org/10.1016/j.gloenvcha.2024.102906
38. Mweemba CE, Amarnath G, van Koppen B. Polycentric LocAl Led Climate AdapTation ChampION (ACTION) to build resilience to droughts in Hanzila Village, Southern Zambia. Colombo, Sri Lanka: International Water Management Institute (IWMI), CGIAR Initiative on Climate Resilience. 2023. 45 p. Available from: https://hdl.handle.net/10568/139488
39. Mweemba C, Amarnath G, van Koppen B. Enhancing drought resilience: Evaluating the livelihood outcomes of a solar-powered water system in Hanzila Village, Southern Zambia. IWMI Research Report 192. Colombo, Sri Lanka: International Water Management Institute; 2025. 50 p.
40. FAO. The State of Food and Agriculture: Migration, Agriculture, and Rural Development. Rome, Italy: Food and Agriculture Organization. 2018. Available from: https://openknowledge.fao.org/server/api/core/bitstreams/0106019d-2529-4f93-b9e5-cce52bee33c3/content
41. Ngoma H, Lupiya P, Kabisa M, Hartley F. Impacts of climate change on agriculture and household welfare in Zambia: an economy-wide analysis. Climatic Change. 2021;167(3–4). https://doi.org/10.1007/s10584-021-03168-z
42. Curry J, Wiegers E, Garbero A, Stokes S, Hourihan J. Gender, HIV/AIDS and rural livelihoods: Micro-level investigations in three African countries [Internet]. UNU-WIDER Research Paper No. 2006/110. 2006 [cited 2025 Oct 14]. Available from: https://www.wider.unu.edu/sites/default/files/rp2006-110.pdf
43. Tembo G, Tembo A, Goma F, Kapekele E, Sambo J. Livelihood Activities and the Role of Livestock in Smallholder Farming Communities of Southern Zambia. Open J Soc Sci. 2014;02(04):299–307. https://doi.org/10.4236/jss.2014.24033
44. Ostrom E. Understanding Institutional Diversity. Princeton (NJ): Princeton University Press; 2005.
45. Ostrom V, Tiebout CM, Warren R. The Organization of Government in Metropolitan Areas: A Theoretical Inquiry. Am Polit Sci Rev. 1961;55(4):831–42. https://doi.org/10.2307/1952530
46. Schlager E, Blomquist W. Embracing Watershed Politics. Boulder, Colorado: University Press of Colorado; 2008.
47. Heikkila T, Schlager E, Davis MW. The Role of Cross-Scale Institutional Linkages in Common Pool Resource Management: Assessing Interstate River Compacts*. Policy Stud J. 2011;39(1):121–45. https://doi.org/10.1111/j.1541-0072.2010.00399.x
48. Pahl-Wostl C, Lebel L, Knieper C, Nikitina E. From applying panaceas to mastering complexity: Toward adaptive water governance in river basins. Environ Sci Policy. 2012;23:24–34. https://doi.org/10.1016/j.envsci.2012.07.014
49. de Stefano L, Welch C, Urquijo J, Garrick D. Groundwater governance in the Rio Grande: Co-evolution of local and intergovernmental management. Water Alternatives. 2018;11(3):824–46.
50. Mulholland E, Berger G. Multi-level governance and vertical policy integration: Implementation of the 2030 Agenda for Sustainable Development at all levels of government. ESDN Quarterly Report 43, January 2017. Vienna, Austria: ESDN Office. 2017. Available from: https://www.esdn.eu/fileadmin/ESDN_Reports/QR_43_final.pdf
51. Nagendra H, Ostrom E. Polycentric governance of multifunctional forested landscapes. Int J Commons. 2012;6(2):104. https://doi.org/10.18352/ijc.321
52. Kozicki ZA, Baiyasi-Kozicki SJS. The survival of mankind requires a Water Quality and Quantity Index (WQQI) and Water Applied Testing and Environmental Research (WATER) Centers. World Water Policy. 2019;5(1):55–70. https://doi.org/10.1002/wwp2.12007
53. Abanyie SK, Ampadu B, Frimpong NA, Yahans Amuah EE. Impact of improved water supply on livelihood and health: Emphasis on Doba and Nayagnia, Ghana. Innov Green Dev. 2023;2(1):100033. https://doi.org/10.1016/j.igd.2023.100033
54. Moriarty P, Butterworth J, van Koppen B, editors. Beyond Domestic. Case Studies on Poverty and Productive Uses of Water at the Household Level. IRC Technical Papers Series 41. Delft, the Netherlands: IRC, NRI, and IWMI. 2004. Available from: https://www.musgroup.net/sites/default/files/Moriarty-2004-Beyond.pdf
55. Renwick M. Multiple Use Water Services for the Poor: Assessing the State of Knowledge. Arlington, VA, USA: Winrock International. 2007. Available from: https://www.musgroup.net/sites/default/files/d852d750a8eafb2fb7ba1427b1c320bd.pdf
56. van Koppen B, Molose V, Phasha K, Bophela T, Modiba I, White M, et al. Guidelines for community-led multiple use water services: evidence from rural South Africa. IWMI Working Paper 194. Colombo, Sri Lanka: International Water Management Institute; 2020. 36 p.
57. Komakech CH. Emergence and Evolution of Endogenous Water Institutions in an African River Basin: Local Water Governance and State Intervention in the Pangani River Basin, Tanzania. [PhD dissertation]. Delft, The Netherlands: UNESCO-IHE Institute for Water Education. 2013. Available from: https://ihedelftrepository.contentdm.oclc.org/digital/collection/phd1/id/43416/rec/9
58. Dahl G, Megerssa G. The sources of life: Boran conceptions of wells and water. In: Palsson G, editor. From water to world-making. African models and arid lands. Uppsala, Sweden: The Scandinavia Institute of African Studies; 1990. p. 21–38. Available from: https://scispace.com/pdf/from-water-to-world-making-african-models-and-arid-lands-37onrgdnp2.pdf

59. Tapela BN. Water Governance in Traditional Rural Communities of South Africa Report on Policy Options for Effective Water Governance in Traditional Rural Communities. WRC Report No. KV 343/15 ISBN 978-1-4312-0697-1. Gezina, South Africa: Water Research Commission; 2015. Available from: https://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/KV%20343-15.pdf

60. GRZ. The Constituency Development Fund Act, 2024 Act No. 1 of 2024. 2024. Available from: https://www.parliament.gov.zm/sites/default/files/documents/acts/ACT%20No.%201%20OF%202024%2C%20THE%20CONSTITUENCY%20DEVELOPMENT%20FUND.pdf

61. Arieko JS, Kisimbii JB. Local community participation in planning and implementation of borehole water projects in Migori County, Kenya. Int J Novel Res Interdiscip Stud. 2020;7(1):1–19.

62. Meaza H, Demissie B, Hermans L, Haftu B, Biruk B, Poesen J, et al. Spatial and seasonal water level dynamics in dryland grabens along the Rift Valley of northern Ethiopia. Hydrol Sci J. 2022;67(9):1418–38. https://doi.org/10.1080/02626667.2022.2085511