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Effectiveness of innovative circular technologies for sustainable rural freshwater supply in Tanzania

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The present study was conducted in two villages situated in the Ruvu–Wami River Basin upstream catchment area in the Kilosa district. The area was experiencing multiple competing water-use activities exacerbated by climate-change-induced human activities and livestock in-migration. Due to the pressure imposed on hydrological resources, new waterpoints were installed while defective ones were not being repaired. The study was guided by two objectives: (a) to investigate the extent to which new innovative circular technologies improved the overall financial sustainability of freshwater schemes and (b) to determine the extent to which financial sustainability contributed to the technical sustainability and overall sustainability of the rural freshwater supply. This study used Lockwood, Bakalian, and Wakeman's eight dimensions of sustainability as a conceptual framework to investigate the extent to which innovative circular technologies increased the financial, technical, and overall sustainability of rural freshwater schemes. Data were collected from 131 households through a quantitative semi-structured survey; these data were complemented by qualitative data involving 116 focus group discussions. One key finding is that the innovative circular technologies demonstrated a capability to increase the financial sustainability of water schemes. However, deficiencies in technical sustainability affected this potential, leading to high dissatisfaction and low expectations among water users. This resulted in various failures, which affected the overall sustainability of the innovative circular technologies, showing the close interrelationship between social acceptance and technological and financial sustainability. Six important recommendations have been made, specifically concerning the importance of financial and technical capacity, community ownership, social acceptance, community participation, change management, and procurement standards, which affect the quality of the physical water infrastructure network.

KEYWORDS

sustainability, rural freshwater schemes, innovative circular water technologies, water circularity, community-owned water organizations (COWSOs), climate change, water stress, Tanzania

1 Introduction

Climate change has had a significant impact on freshwater availability to sustain human development. The United Nations has deliberated and identified the whole area of freshwater-use efficiency through conservation and circularity to be an important priority for sustainable development. The United Nations (2023) Sustainable Development Goal 6.4 was set to ensure that by 2030, a substantial increase in water-use efficiency would be achieved across all sectors by ensuring sustainable withdrawals and supply of freshwater to address growing scarcity, including through the increased deployment of innovative circular technologies. This was done to address concerns that global demand for freshwater would exceed viable resources by 2030 if nothing was changed (CE100, 2019; Qadri and Bhat, 2020; Global Environment Facility, 2023).

Freshwater is a critical resource facing increasing scarcity globally. Global water demand has outpaced supply, particularly during dry seasons. Although 70% of Earth is covered by water, only 2.5% is freshwater, while 70% of it is frozen as ice caps in the Arctic, Antarctica, and Greenland (United Nations, 1997; Qadri and Bhat, 2020). The rest is found in different locations including as soil moisture, or in deep underground aquifers as groundwater, as well as surface water. Among this water, one-third is found in lakes, rivers, reservoirs, and groundwater sources that are shallow enough to be tapped at an affordable cost (United Nations, 1997; Qadri and Bhat, 2020; Global Environment Facility, 2023).

In order to address this challenge, improving water conservation and circularity is essential. To this end, Tanzania has recognized the importance of water-use efficiency and sustainable withdrawals to ensure freshwater availability for future generations. Tanzania's 2002 Policy adopted a strong connection between the principles of devolution, operation and maintenance (O&M), circularity, and sustainability. This includes the ability of freshwater schemes to conduct ongoing O&M of physical water infrastructure by transfer to community-level water schemes control from public authorities to Community-Owned Water Supply Organizations (COWSOs; United Republic of Tanzania, 2002; United Republic of Tanzania, Ministry of Water, 2007; United States Agency for International Development - Sustainable Water Partnership, 2019).

Significant gaps hindered freshwater sustainability in Tanzania. These included weak management and governance of freshwater schemes, financial sustainability to support service delivery, and neglect of infrastructure maintenance and rehabilitation (Harvey and Reed, 2006; Haysom, 2006; Foster, 2013; Anders et al., 2019; Global Environment Facility, 2023).

According to the United Nations Department of Economic and Social Affairs (2022), there is an urgent need to promote freshwater availability through *inter alia,* innovative circular technologies. These measures could be deployed using innovative circular technologies, such as artificial intelligence (AI), the Internet of Things, Big Data, and robotics to optimize irrigation, improve water-smart agricultural practices that reduce evaporation, and promote the efficient management of domestic water use. Other measures that can be taken are transboundary water cooperation and water-sharing agreements (Grumbach and Hamant, 2020; Mollah, 2023; One World, 2023; Hoosain et al., 2023; Sanchez-García et al., 2024).

There is a need to place much more emphasis on the efficiency of freshwater consumption through recycling and reuse (Grumbach and Hamant, 2020). This can be achieved by increasing water circularity including through the adoption of innovative circular technologies. The Tanzania 2002 water policy places emphasis on promoting by controlling water loss, depletion, and pollution through the deployment of more efficient water-use management and technologies. Low water conservation efficiency was found to be prevalent in many irrigation schemes (10–15% of freshwater loss) and leakages from domestic supply schemes (52% of freshwater loss).

The 2002 Water Policy was based on the principle that greater devolution would provide greater ownership, especially concerning ongoing operation and maintenance (O&M). Innovative circular solutions were later introduced to implement circular business models that promote efficiency and sustainability through sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products for as long as possible (Stavropoulos et al., 2021). The idea is to prevent waste and instead to reuse it in production.

Increased O&M contributes to increased freshwater circularity by promoting efficiency, reduction in water loss, leakages, illegal connections, water source conservation, misuse, and wastewater recycling (Oduor, 2019). Combined, these freshwater circularity factors contribute to increased freshwater sustainability.

The study used Lockwood et al. (2003) eight dimensions of sustainability as a conceptual framework. According to Lockwood et al. (2003), financial, technical, technological, community, social, institutional, policy, and environmental factors are the eight main types of factors affecting post-project sustainability in rural water supply.

According to Lockwood et al. (2003), financial sustainability in the context of rural water supply refers to the ability of a water supply system to generate sufficient revenue to cover its operational and maintenance costs in the long term. This includes the ability to collect user fees, manage finances effectively, invest in future upgrades, and make replacements. In other words, a project's financial sustainability may be affected by one or more of Lockwood et al. (2003) dimensions of sustainability. For example, a scheme's financial sustainability may be affected by low levels of technical sustainability—even when there is an efficient and supportive water infrastructure network in place, it may still fail if it does not have the technical expertise to support routine O&M, including the installation, operation, and maintenance of available innovative circular technologies (Reynolds, 1992; Parry-Jones et al., 2001; United Republic of Tanzania, 2002; Harvey and Reed, 2006; Pals, 2011; Sanga, 2015). Similarly, tariff setting for user fees, collection systems, control measures and management, governance, and transparency can affect a project's financial sustainability even when the other dimensions mentioned by Lockwood et al. (2003) are functional (WELL, 1998; Webster et al., 1999; Pals, 2011; Kirenga et al., 2018).

According to Lockwood et al. (2003), social and community structures play an equally important role in post-project sustainability. Social, cultural, and gender dynamics affect the extent of community participation from the initial stages of a project. The extent to which communities participate in a project determines their level of ownership and long-term sustainability. The level of ownership, on the other hand, determines the willingness of community members to contribute to a project (Lein and Tagseth, 2009). Furthermore, the extent of the willingness of community to contribute determines the extent to which O&M is practiced and, by extension, the long-term physical condition of the water scheme. Ultimately, a functional scheme enhances consumer satisfaction, which impacts ownership, willingness to sustain the system, and by extension, sustainability (Lockwood et al., 2003; Haysom, 2006; Pals, 2011). According to Lockwood et al. (2003), ownership can only be realized if an informed choice is made based on whether individuals feel they were adequately involved in deciding the costs of O&M. Lockwood et al. (2003) sustainability checklist is considered in addressing the following eight research topics.

i Project initiation: This is the extent to which community members feel responsible for initiating a project, as opposed to being selected by a project sponsor or government.
ii Informed choice: This indicates how individuals feel they were informed about the implications of decisions made in terms of costs and responsibility for O&M.
iii Contribution: Contributions to the initial capital investment, including cash, labor, and in-kind contributions.
iv Physical condition: The physical condition of the water system is based on factors such as construction quality, pressure levels, and leaks or defects in the masonry or pipes.
v Consumer satisfaction: Consumer satisfaction with the water service is based on consumers' opinions on factors such as the quantity and quality of water, its taste and color, and the continued use of alternative sources.
vi O&M practices: This indicates whether the community has a designated system operator, immediate access to tools and spare parts, and information about follow-up support.
vii Financial Management: This denotes the extent to which each community member has access to financial records.
viii Willingness to sustain the system: This is the degree to which community members feel responsible for the maintenance (and, therefore, the sustainability) of a scheme.

This study was conducted to assess the effectiveness of innovative circular technologies in sustaining rural freshwater supply in Msowero and Mvumi villages in the Kilosa District in Tanzania. The study was conducted to investigate the following objectives:

i To investigate the extent to which new innovative circular technologies improve the overall financial sustainability of community-owned freshwater schemes.
ii To examine the extent to which financial sustainability contributes to technical sustainability and the overall sustainability of rural freshwater supply from the community-owned schemes.

An illustration of the interrelationship between the conceptual frameworks and study objectives is presented in Figure 1.

2 Status of freshwater policy and management in Tanzania

The 2002 Water Policy recognizes freshwater as a basic natural resource that sustains life and contributes to various social and economic activities (United Republic of Tanzania, 2002). In practice, the importance of water resources to the overall national economy is significant, contributing to 60% of Tanzania's gross domestic product (GDP), which is nearly enough for the country's development needs (WaterAid, 2024). According to the World Bank (2019a,b), 89% of water withdrawals are for agriculture, 10% is for domestic consumption, and only 1% is for industry despite the industrial sector

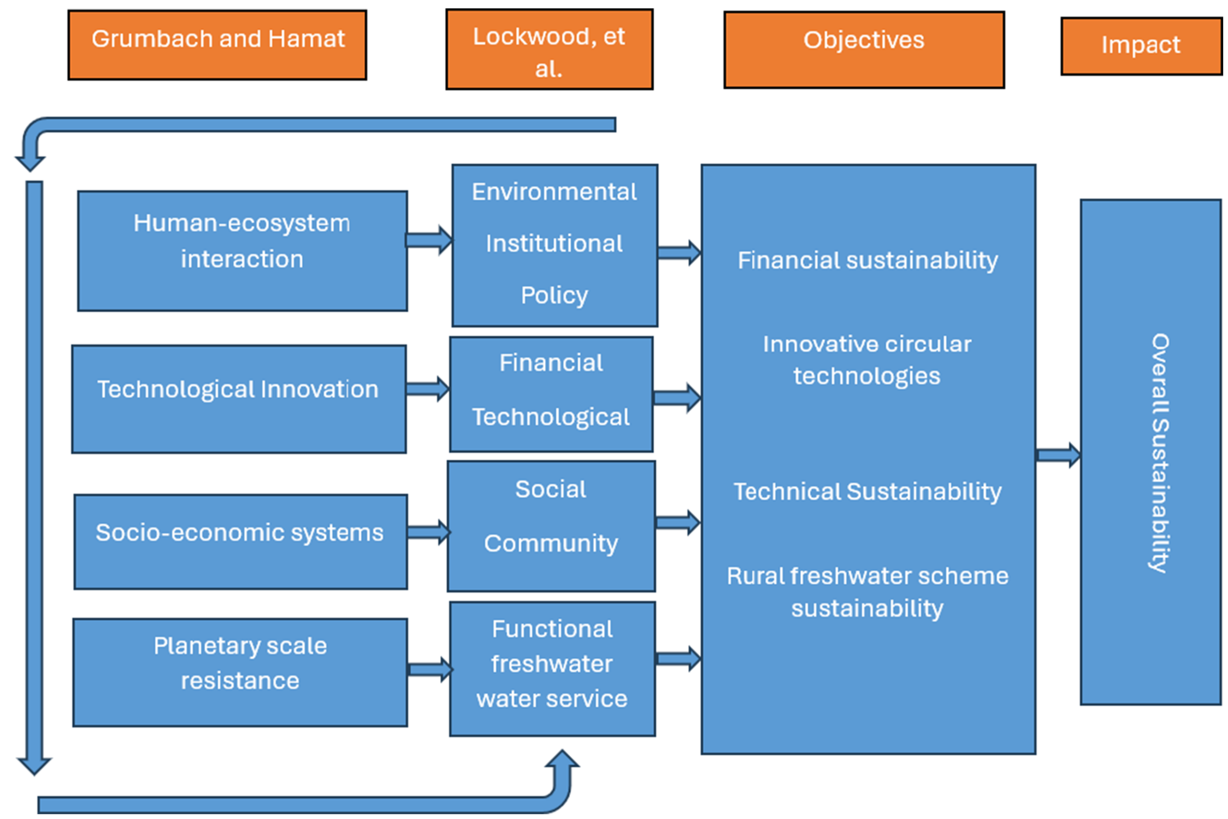


FIGURE 1
Interrelationship between conceptual frameworks and study objectives.

being predominantly agro-processing, making it highly dependent on water. Overall, 40% of energy generation comes from hydropower, which has been operating below capacity due to upstream withdrawals (World Bank, 2019a,b) According to Oringa et al. (2020), declining water resources are a risk to Tanzania's overall socioeconomic growth. The impact of water scarcity is likely to be felt in rural areas and aggravated by climate change, aridity, and among poor households.

Total global water resources are approximated to be 1.385 billion km^3, of which 2.5% is freshwater and 97.5% is saline (Kundzewicz, 2007; Qadri and Bhat, 2020). The United Nations has deliberated and identified the whole area of freshwater-use efficiency through conservation and circularity to be an important priority for sustainable development. The United Nations (2023) Sustainable Development Goal 6.4 was set to ensure that by 2030, a substantial increase in water-use efficiency would be achieved across all sectors by ensuring sustainable withdrawals and supply of freshwater to address growing scarcity, including through the increased deployment of innovative circular technologies. This was done to address concerns that global demand for freshwater would exceed viable resources by 2030 if nothing was changed (CE100, 2019; Qadri and Bhat, 2020; Global Environment Facility, 2023).

This dilemma was expressed in Grumbach and Hamant (2020) concept of suboptimality as a state where individual elements or components of an ecosystem operate less than perfectly or in a less-than-optimal way. However, they further argued that, despite these individual inefficiencies, there are still pathways, which can ensure the overall system can still exhibit robustness and resilience. Key factors contributing to Grumbach and Hamant (2020) concept of suboptimality include randomness, heterogeneity, slowness, and redundancy. However, interdependencies between these suboptimal components are crucial to achieving relative optimality. These interdependencies can lead to second-best optima at the global level, meaning that the system as a whole may reach a satisfactory state even if individual components do not operate at their peak efficiency. Sub-Saharan Africa (SSA) is among the regions with the lowest rate of water-use efficiency. This suboptimality results from unsustainable withdrawals amid deteriorating quality due to pollution, waste, and a lack of water conservation and circularity. Tanzania, for example, has reached a water stress level of 12.96% (United Nations, 2020), which is well within the low–medium stress range (10–20%). Tanzania's renewable freshwater resources have declined by 53% over the past 25 years, from 3,000 to 1,600 m^3 per person per year (World Bank, 2019b; World Bank, 2019a). This translates to a colossal loss of 1,400 m^3 per person per year over the past 25 years, translating to an annual loss of 56 m^3 per person per year. Going by this rate, the water stress indicator of 1,700 m^3 per person per year will be reached in 2 years, and the more acute water scarcity indicator of 1,000 m^3 per person per year in a decade.

This water stress indicator is based on the availability of water up to 1,700 m^3 per person per year. If there is less than 1,700 m^3 available per person per year, then the area is classified as water-stressed (Fluence, 2022). Water stress occurs when the demand for water exceeds the available amount. Water stress is compounded when poor quality restricts its use. Water stress levels have increased over time due to expansions in the economy (which has tripled) and formal and informal irrigation while increasingly relying on the use of over-stressed water resources for hydroelectrical power generation. Water demand has exceeded the dry season supply by up to 150% in some areas, and this gap can only be filled by improving water conservation and circularity (World Bank, 2019b; World Bank, 2019a).

According to the United Nations Department of Economic and Social Affairs (2022), there is an urgent need to promote freshwater availability through *inter alia*, innovative circular technologies. Conservation and circularity need to be prioritized in the agriculture sector (which accounts for 70% of withdrawals); industry and energy (20%); and the domestic sector, cities and ecosystems to encourage recharging (United Nations Department of Economic and Social Affairs, 2022). Additional water circularity measures could be used to promote conservation such as the construction of dams to contain water lost through surface runoff, desalination, water reclamation, drip irrigation, and reuse. These measures could be deployed using innovative circular technologies such as artificial intelligence (AI), the Internet of Things, Big Data, and robotics to optimize irrigation, improve water-smart agricultural practices that reduce evaporation, and promote the efficient management of domestic water use. Other measures that can be taken are transboundary water cooperation and water-sharing agreements (Grumbach and Hamant, 2020; Mollah, 2023; One World, 2023; Hoosain et al., 2023; Sanchez-García et al., 2024).

Given the importance of freshwater to the national economy, ongoing trends in the wake of climate change call for increasing attention to the treatment of freshwater resources as part of the broader circular economy. This means to emphasize efficiency in its consumption through recycling and reuse (Grumbach and Hamant, 2020). This can be achieved by increasing water circularity including through the adoption of innovative circular technologies. According to the United Republic of Tanzania (2002), freshwater circularity could be promoted by controlling water loss, depletion, and pollution through the deployment of more efficient water-use management and technologies. Low water conservation efficiency was found to be prevalent in many irrigation schemes (10–15% of freshwater loss) and leakages from domestic supply schemes (52% of freshwater loss). According to Grumbach and Hamant (2020), conserving water resources ensures its availability for future generations. By cooperating, water users can create a more sustainable environment for everyone. Individual sacrifices contribute to the overall resilience of the water system and ensure its sustainability. The goal is to find a balance between individual needs and the collective good. In essence, this statement implies that while individuals may have incentives to maximize their water use, it is often in the best interest of the community as a whole to adopt a more cooperative and sustainable approach (Carter et al., 1999). By limiting individual consumption and working together, COWSOs help ensure the long-term viability of water resources for future generations.

The sustainability question of freshwater schemes was found to be significant by Taylor (2009) after finding that 46% of waterpoints in rural communities in Tanzania were non-functioning (World Bank, 2019a,b). Whereas the target was to reach 80% of the rural population with clean drinking water, only 65% was reached. Moreover, 25% of publicly improved waterpoints were non-functional within 2 years of installation (Joseph et al., 2019; WaterAid, 2024). Whereas much attention and resources were given to the connection of new waterpoints, the sustainability of these waterpoints has stood out as a problem that no one was addressing. If this problem remains unanswered, it will not be possible to meet water sustainable development goals if new projects leave about half of all waterpoints unable to function (United Republic of Tanzania, Ministry of Water, 2007; Taylor, 2009; Joseph et al., 2019; United Nations, 2019; United Republic of Tanzania, 2021). The question then becomes whether policy attention should be given to increasing new connections while turning a blind eye on the sustainability of existing waterpoints.

A key challenge facing freshwater sustainability in Tanzania lies in the management and governance of freshwater schemes (Harvey and Reed, 2006; Haysom, 2006; Foster, 2013; Anders et al., 2019; Global Environment Facility, 2023) In order to achieve this, some form of community scheme organization is needed. This is in response to Pals (2011), who argued communities could hardly maintain their own waterpoints sustainably without some form of organization. In consequence, a policy decision was immediately made through the 2002 National Water Policy to transfer community-level water schemes control from public authorities to Community-Owned Water Supply Organizations (COWSOs; United Republic of Tanzania, 2002; United Republic of Tanzania, Ministry of Water, 2007; United States Agency for International Development - Sustainable Water Partnership, 2019); this policy is still in effect at the time of this publication. This orientation to community control was driven by the three principles of devolution, ownership, and sustainability (United Republic of Tanzania, Ministry of Water, 2007; Lein and Tagseth, 2009; Kirenga, 2019). The policy was based on the principle that greater devolution would provide greater ownership, especially concerning ongoing operation and maintenance (O&M). Increased O&M contributes to increased freshwater circularity by promoting efficiency, reduction in water loss, leakages, illegal connections, water source conservation, misuse, and wastewater recycling (Oduor, 2019). Combined, these freshwater circularity factors contribute to increased freshwater sustainability.

What had not been envisaged by the 2002 Water Policy was the role innovative circular technologies could play in reinforcing its three principles of devolution, ownership, and sustainability. The United States Agency for International Development—Sustainable Water Partnership (2019) argued that new available technologies have an important role to play in enabling COWSOs to strengthen devolution, ownership, accountability, and sustainability. The term *innovative circular technologies* refers to the use of new smart technological solutions to implement circular business models, which involve sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products for as long as possible (Stavropoulos et al., 2021). The idea is to prevent waste and instead to reuse it in production.

The 2002 Water Policy made a strong connection between the principles of devolution, O&M, circularity, and sustainability. This includes the ability of freshwater schemes to conduct ongoing O&M of physical water infrastructure. This leads to increased freshwater circularity through the reduction in water loss, leakages, illegal connections, water source conservation, control of misuse, and wastewater recycling. It is further recognized that the sustainability of services provided by freshwater schemes effectively contributes to the circular economy through the preservation of freshwater against contamination from multiple uses of water resources; uncontrolled pollution; intermingling with livestock, wildlife, human feces, and algae development; reduction in water loss through leakages; illegal connections; misuse; uncontrolled wastewater disposal; and recycling in the wake of ongoing scarcity amid climate change (Ngige and Macharia, 2006; Tadesse et al., 2013, Tonya and Mpangala, 2015). According to Haysom (2006), the issue of freshwater sustainability is not just about designing and utilizing innovative circular technologies but also contributes to the overall ongoing availability of clean, affordable, and accessible freshwater for the general population and economic activities. This argument was supported by the analysis in the seminal work by Grumbach and Hamant (2020) who suggested that human societies, such as water users cooperating in COWSOs, often prioritize collective interests over individual ones. This principle, which was observed in their analysis of both biological and technological systems, suggests the importance of cooperation as overconsumption by one individual can negatively impact the availability of resources for others. They also called for the use of technology-driven solutions, which offer answers to resource scarcity, pollution, or the climate crisis.

Despite efforts, it immediately became apparent that COWSOs were a weak mechanism for efficient freshwater scheme management and operations (Awinia, 2019, 15–17). Key areas of concern were cash management, record keeping, accounting, and reporting. Weak financial management contributed to financial mismanagement, the concealment of financial records, a lack of transparency, and a reduction in confidence across the water user community (Masaya, 2014; Mayo and Nkiwane, 2013; Riswan and Bushra Beegom, 2020; Tonya and Mpangala, 2015). The overall effect was low user satisfaction and a decreased willingness to pay, resulting in service disruptions (Awinia, 2019).

The United Republic of Tanzania (2002) identified seven prerequisites for freshwater scheme sustainability. These included the level of community ownership, achievement of full cost recovery for O&M, availability of spare parts and expertise, protection of water sources, compatibility of technology with capacity of beneficiaries, and recognition of women as key players (WELL, 1998; United Republic of Tanzania, 2002; Mackenzie and Isha, 2005; Mommen et al., 2017; Joseph et al., 2019).

The contribution of innovative circular technologies in promoting freshwater scheme sustainability through improved efficiency, governance, and circularity was recognized by the Tanzania Water Assessment conducted by Oringa et al. (2020). They were also recognized by Grumbach and Hamant (2020), who argued technological advancements in conservation should be embraced, especially as environmental challenges intensify. Humanity might seek to exert more control over the conservation of nature through advancements in innovative technologies. Human intelligence, augmented by machine intelligence, has grown such that its capacity to overcome limitations faced by our planet has become virtually limitless, and this capacity should be more effectively harnessed. The emergence of smart technologies could offer solutions to problems related to resource scarcity, pollution, and climate change. Oringa et al. (2020) identified such technologies to include smart meters, water "automated teller machines" (ATMs), and prepaid meters.

Despite this potential, a number of challenges still face operationalization of innovative circular technologies. These include long gestation and payback periods, the need to take into account the architecture of the broader system and the condition of the corresponding water physical infrastructure (Carter et al., 1999). Solutions to these issues are often lacking in rural freshwater schemes. According to Oringa et al. (2020), the underperformance of smart meters installed by E-WaterPay Ltd. compared to similar prepaid meters was attributed to failures in the wider infrastructure support network.

From the beginning, the involvement of communities in the operation of innovative circular technologies—including their involvement in financial contribution—instilled overall, long-term ownership, trust, and technical expertise. This played an important part in their sustainability. Carter and Ross (2016) reported that the sustainability of innovative circular technologies is usually enhanced when managed by the users themselves with the help of local government authorities (LGAs), private providers, and non-government organizations (NGOs).

3 Materials and methods

This section details the methodological approach, including data sources, collection methods, sampling procedures, analytical techniques, and ethical statement to justify credibility and trustworthiness of the findings.

3.1 Data sources

This study drew data and information from the secondary and primary data sources described below.

3.1.1 Reports, files, and records

The study relied on available data sources such as files, records, and registries kept by freshwater schemes and its service provider, E-WaterPay Ltd. The records included quarterly physical and financial reports, minutes of the annual general meeting, access to the electronic E-WaterPay Ltd dashboards, freshwater scheme logbooks, and USAID-WARIDI (Water Resources Integration Development) project documents. Published materials and case studies were collected through desk research involving empirical studies, technical reports, empirical studies published in peer-reviewed scientific journals, case studies from other countries, and other literature sourced from websites, internet search engines, and libraries[1] as well as Accelerating Scale-up of SmartTechs in water in Tanzania.[2] In total, 48 publications were cited 79 times to inform the introduction and literature review sections of this publication. Out of these, 33 were cited from empirical peer-reviewed journals, 11 from public and international organization reports, and four from official government reports.

3.1.2 Service provider dashboard

Further secondary data in the form of information on the quantity of water purchased, consumption trends among *e-tag* owners, their distribution by freshwater schemes, and waterpoints (per month and year) were obtained from the service provider's dashboard and analyzed. *E-tags* were coin-shaped plastic e-wallets that could be recharged using mobile money service (MMS) through mobile phones. The tags unlocked the e-water meters, which then released water while deducting charges.

The study developed a checklist known as the data analysis plan, which outlined the different indicators from the dashboard of the service provider. The service provider offered additional data and information on the indicator checklist which indicated additional inputs.

1 www.documents.worldbank.org
2 www.smartcentretanzania.com

3.2 Primary data sources

This study followed a quantitative and qualitative mixed-methods approach for data collection. This involved complementary methods using different data sources ranging from a quantitative semi-structured questionnaire to an open-ended qualitative interview guide. The latter allowed an in-depth discussion to explore underlying dynamics and contextual issues surrounding the adoption of innovative circular technologies. The triangulation of data sources allowed one data source to offset the limitations of another. The closed-ended quantitative questionnaire provided a static picture of water users' perceptions at the time of the interview, while the open-ended questions provided detailed in-depth information on underlying context and motivation factors.

3.2.1 Quantitative semi-structured household questionnaire interviews

Quantitative semi-structured questionnaires were administered to water user households. The questionnaire had both closed- and open-ended questions. Closed-ended questions had predefined answers which were created during the design of the tool. Open-ended questions were set to collect additional personal views from the study respondents.

3.2.2 Focus group discussions

Open-ended in-depth interviews with various community group members, COWSO leaders, WARIDI project staff, and district water supply department staff were conducted in the form of focus group discussions (FDGs).

3.2.3 Key informant interviews

The open-ended interview guide was also used to administer the key informant interviews (KIIs) targeting specific resource persons and subject-matter specialists with knowledge about freshwater sustainability.

3.2.4 Observation study

Non-participant observation was conducted in the form of transect walks across the water scheme area from catchment to waterpoints. The observation study was open-ended without prescribed criteria. This involved observations of the way communities used innovative circular technologies at waterpoints, how waterpoints were functioning, and interactions. Observations also noted multiple alternative water uses for different socioeconomic activities, which polluted freshwater resources, as well as opportunities for circularity and conservation.

Observation studies were useful in comparing waterpoint functionality differences between upstream and downstream areas.

3.3 Sampling

A six-stage stratified sampling framework was chosen to enable the use of various sampling methods within the different strata.

The study used purposive and random sampling procedures for the first, second, third, and fourth sampling stratum; it used random sampling procedures for the fifth and sixth.

3.3.1 Purposive judgmental sampling procedure

First, the Ruvu–Wami River Basin was purposively selected because it was experiencing water stress due to multiple competing water-use activities. This basin covers 67,100 km^3, has a population of 10 million people, includes two major urban areas, and services various economic needs, including domestic (345 m^3), irrigation (682 m^3), hydropower (2 m^3), livestock and aquaculture (34 m^3), industries and mining (78 m^3), and ecosystem and wildlife (298 m^3; United Republic of Tanzania, 2020).

Second, the Msowero ward was chosen as it lies in the catchment area of the Ruvu–Wami Basin. It was also being threatened by multiple competing water uses including sugarcane plantation, in-migration by pastoralists and their livestock, and a burgeoning urban enclave resulting from proximity to a major road junction.

Third, the villages of Msowero and Mvumi were purposively chosen based on four criteria. First, they lie within the Msowero ward. Second, they were both located in an area where there was a high concentration of freshwater tributaries to the Ruvu–Wami River Basin. Third, they both had freshwater schemes. Fourth, they were both piloting innovative circular technologies for more than a period of 6 months.

Fourth, waterpoint zones were purposively selected to achieve diversity and heterogeneity. The waterpoints were first clustered into eight zones (four zones for each village). The clustering was based on shared characteristics such as orientation from water sources and overhead tanks, concentration of users who already had *e-tags*, distance between taps, gravitational range from overhead tanks, and functionality rates of waterpoints. The waterpoints had been connected to innovative circular technologies and were selected from each village based on the median number of available waterpoints. Figure 2 shows the distribution of sampled waterpoints in the villages of Mvumi and Msowero.

3.3.2 Random sampling procedure

The fifth sample stratum comprised waterpoints. The random ballot sampling procedure was used to select the waterpoints, while respondents from households were selected through a simple random procedure.

Ballot sampling involved writing the names of all waterpoints in a zone on separate but similar-looking pieces of paper and then throwing them like dice on the floor. Community members or study enumerators then randomly picked pieces of paper to select the actual taps to be evaluated.

The sixth and final sample stratum involved the selection of households from within the waterpoint catchment area, which was obtained through simple random sampling. In the end, the study sample comprised 131 quantitative semi-structured household questionnaires. These included 69 from Mvumi and 62 from Msowero (see Table 1; Figure 3).

The study also involved 116 unstructured qualitative interviews (see Tables 2, 3).

In addition, KIIs were conducted (see Table 3).

3.3.3 Data analysis tool

This study used the Statistical Package for Social Sciences (SPSS) for analyzing the quantitative semi-structured survey questionnaire responses. The questions were first created in SPSS, followed by data entry and analysis. A data analysis plan was prepared to guide the analysis of the variables.

Qualitative data from FGDs and KIIs were transcribed into interview transcripts. The transcripts were then analyzed manually through taxonomic domain analysis. This method involved the identification of similar themes from the field notes, followed by an analysis of the relationships between the themes.

Finally, Generative AI technology, especially the Google search engine and Gemini, was used by the author for background research and language editing.

3.3.4 Ethical statement

The study has been reviewed by the ethics committee of the Open University of Tanzania (OUT). The study objectives were read aloud, and the respondents were given the opportunity to

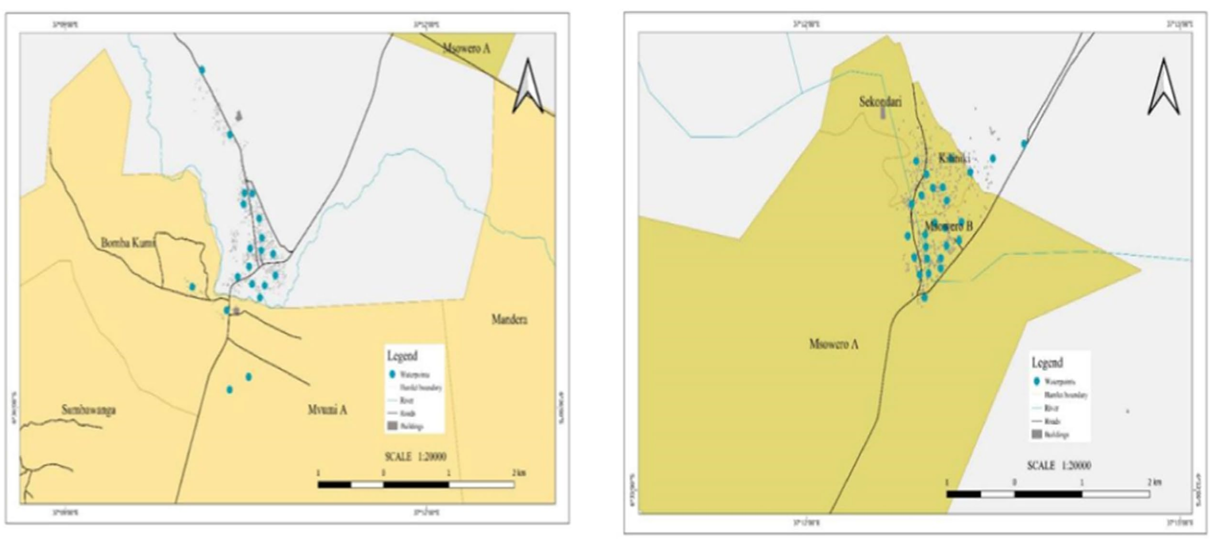


FIGURE 2
Distribution of water-points in the case study villages. Source: Sample analysis of the study survey.

TABLE 1 Sample framework for the quantitative structured questionnaire survey.

Zone	Mvumi			Msowero		
Zone	No. of taps	Sampled taps	H/hold interviewed	No. of taps	Sampled taps	H/hold interviewed
1	7	2	19	9	4	17
2	6	0	16	6	2	14
3	3	2	18	7	1	19
4	51	4	16	4	1	12
Total	21	7	69	26	8	62

Source: Sample analysis of the study survey.

express their understanding and give their consent. The respondents were informed that all responses would be kept confidential and only be referred to collectively as a representative group. This publication is based on a conference paper that was originally presented virtually at the *International Conference on Circular Economy: Redefining the World and Driving towards Sustainability* held on 18–19 May 2022 at the MIT World Peace University School of Economics based in Pune City, India. Some of the findings were drawn from an evaluation survey conducted by the author on the functionality of innovative circular technologies in freshwater schemes which were supported by Resonance Global Market Solutions in the United States. Other than this, there was no involvement of an external funding source in the research design, interpretation of data, writing, or submission for publication.

4 Results

The two case study villages were part of a pilot project to implement an innovative water circular technology to transform water sales from a cash-fee collection system to purchase water credit using rechargeable, internet-powered *e-tags*.

Generally speaking, the study found that the introduction of innovative circular technologies was transformative as it relates to freshwater conservation and sustainability. The technology increased the prospect of financial sustainability by improving financial management and control. The technology linked the internet and mobile phones to collect water fees, by transferring directly from a water user to an *e-tag*. It subsequently transferred the fees to a dashboard and then directly to the bank. This ensured a more transparent process of fee collection than the previous cash-for-sale system in which financial mismanagement was rampant. Innovative circular technologies circumvented previous channels of mismanagement and ensured the availability of prompt O&M funds and, by extension, sustainability.

The study established generally satisfactory levels of financial improvement, especially in the Msowero scheme. Additionally, the freshwater schemes were consistently receiving monthly payments deposited into their bank accounts by the service provider, as shown in Table 4.

This was a departure from the previous high prevalence of under-reporting under the cash-for-sale system, which had left the schemes virtually unable to garner sufficient funds for O&M and, therefore, to sustain services. Increased financial sustainability enabled the schemes to increase the technical maintenance of the physical water infrastructure network, thus enabling them to sustain services.

Despite these benefits, the introduction of innovative circular technologies did not go without problems. More than half of the waterpoints in Mvumi were non-functioning.

There were a number of prerequisite factors that caused the technologies to fail in Mvumi, where 52.5% of waterpoints were non-functioning (Table 5).

The study revealed the unsatisfactory condition of the physical water infrastructure contributed to the complete sustainability failure of the innovative circular technologies in Mvumi. Several related factors seemed to contribute to non-performance. It was inferred from interviews with scheme leaders and technicians that the innovative circular technology used in Mvumi was generally technically functional, with the exceptions of those which were in areas where there was low water pressure from overhead tanks—in Figure 4, the red dots indicate non-functioning waterpoints, and the blue dots indicate functioning ones.

It can be seen from Figure 4 that there was a positive relationship between distance from the center of the water scheme where the overhead tanks were located on a hill and the location of waterpoint malfunctionality. Through interviews with scheme leaders and technicians, the study established that the functionality of innovative circular technologies depended on the integrity of the physical condition of the physical water infrastructure.

It was further established that the source of low water pressure from overhead tanks was caused by leakages. These leakages resulted from the puncturing of distribution pipes due to poor procurement, resulting in the installation of substandard tanks, puncturing and tearing due to poor handling during offloading, and lifting. The same was true of technical deficiencies of substandard distribution pipes. The recommended depth of furrows to lay distribution pipes was also not followed. This led to over-exposure, overheating by sunlight, heat conduction through the soil, and eventual rupture, leakage and water loss. These anomalies were caused by weak institutional capacity. *Institutional capacity* refers to the ability of schemes to procure physical infrastructure that meets required specifications, quality and standards, as well as procurement procedures. Weak institutional capacity was found to have a direct negative effect on the technical functionality of the freshwater scheme and, therefore, its ability to provide services.

Water pressure was observed as an important characteristic of the functionality of the innovative circular technologies. A minimum level of pressure was needed to thrust open the e-water meters when prompted by the *e-tags*. Without this pressure, the e-water meter could not function.

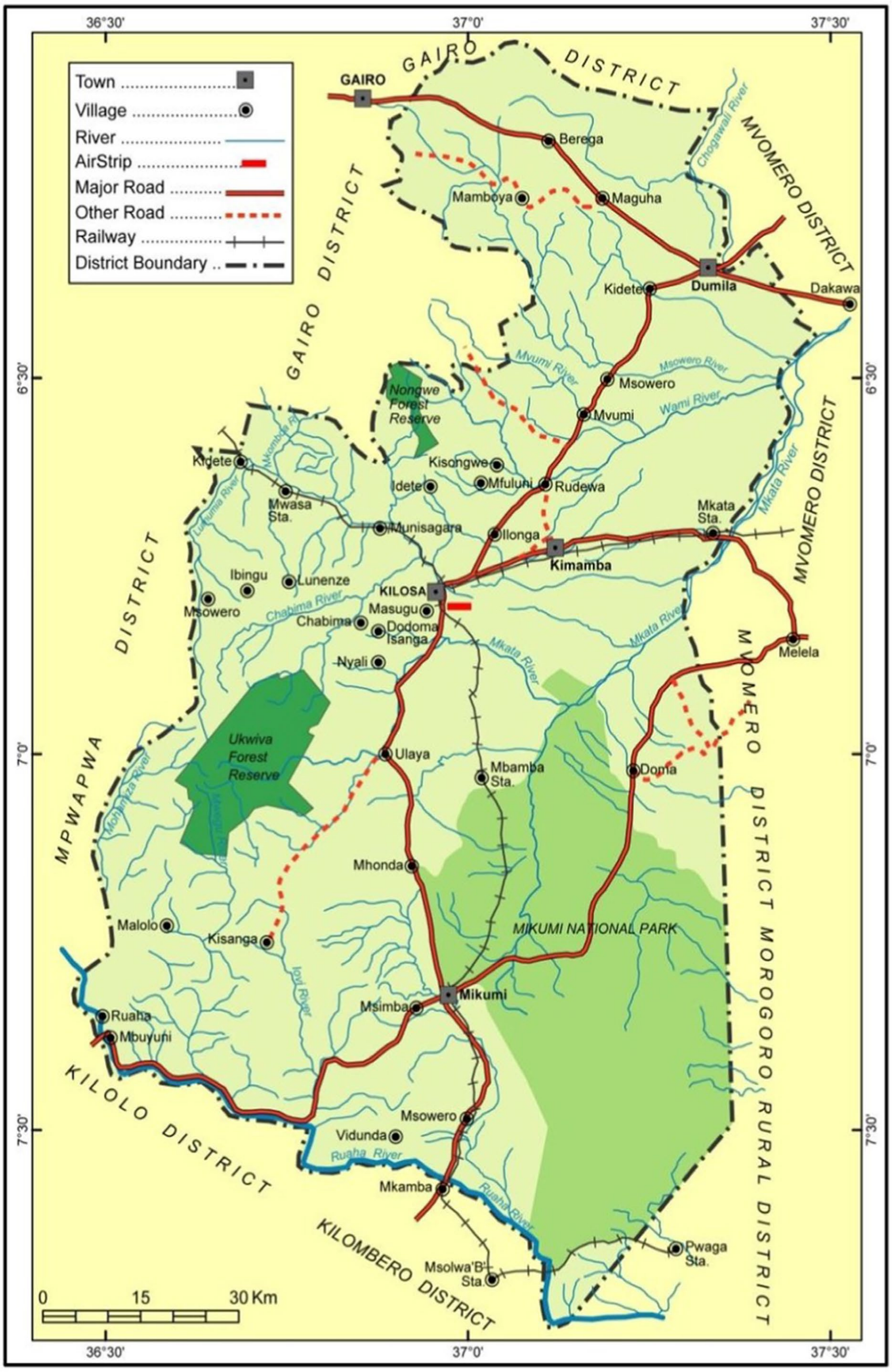


FIGURE 3
Map of the Kilosa District (with Mvumi and Msowero villages).

The factors mentioned above had a profound effect on the circularity and conservation of freshwater in Mvumi. The study was informed by scheme leaders that the service provider had made efforts to provide full-time standby technicians to ensure technical sustainability through provision of on-spot O&M in order to maintain the required level of water pressure to reach malfunctioning prepaid meters. In addition, the service provider kept on stand-by one to two complete spare prepaid meters for prompt replacement in case there was a breakdown. An immediate automated notice was provided electronically to technicians in the event of a broken or leaking pipe or when water was not being sent. However, although the *e-tag* dashboard alerted leakages in Mvumi, the high prevalence of weak, torn, and leaking pipes contributed to the low impact of the alert system. All these efforts, however, were futile because the operation of the innovative circular technologies depended on a required level of pressure, which could only be ensured by the integrity of the physical water infrastructure. The service provider further upgraded prepaid meters to improve their connectivity in order to improve notification

TABLE 2 Type of FGD groups and numbers of respondents.

Respondents	Mvumi	Msowero
Freshwater schemes leaders	6	9
Water users	16	24
Community members who did not have e-tags	5	7
Water technicians	1	2
Vulnerable group members	8	3
Children who are sent to fetch water from MMS-metered pipes	3	8
MMS sales agents	1	4
Community elders	4	2
Private connection (PC) customers	2	0
Ward/village officials	1	1
Total	48	59

Source: Sample analysis of the study survey.

TABLE 3 Type of KII groups and numbers of respondents.

Category of interviewee	No. of respondents
MMS technician	1
WARIDI staff	6
WARIDI chief and deputy	2
District water engineer	1
Total	9

Source: Sample analysis of the study survey.

TABLE 4 Outputs achieved during innovative circular technologies partnership pilot phase.

Planned output	Mvumi	Msowero
No. of waterpoints installed with innovative circular technologies	26	21
No. of households that received an e-tag	1,571	3,899
No. of households that have ever utilized innovative circular technology	1,553	3,421
Total liters collected	1,402,418	19,498,695
Total revenue earned (USD)	1,276	15,220

Source: Service provider's dashboard water operator monthly revenue statement.

TABLE 5 Analysis of non-functionality of community pipes over the pilot period (%).

Water scheme	Baseline	Interim	Final
Mvumi	47.6	38	52.3
Msowero	3.8	0	0

of emerging technical hiccups. In Msowero, this automated notification contributed to immediate O&M of water infrastructure. Prompt maintenance of the physical water infrastructure network in Msowero effectively contributed to the technical sustainability of the freshwater scheme and consequent water services.

The link between internet connectivity, water pressure, timely O&M, and non-functionality of innovative circular technologies was observed through physical examination. It was established that Mvumi has three sets of overhead tanks where one was a big concrete tank of 25 m^3, which was constructed in the 1970s, and two others were smaller (5 m^3) plastic tanks put in place shortly before innovative circular technologies were introduced. Innovative circular technology meters which were installed in the distribution line that fed from the bigger 25-m^3 tank were well functioning. Those which fed from the smaller tanks, particularly those further downstream, were dysfunctional. This observation prompted the study to focus on water pressure as the main contributing factor to the non-functionality of innovative circular technologies.

This finding was collaborated by FGDs where water users pointed to the quality of the physical water infrastructure as the main determining factor of sustainability. The size and type of water tank and weak plastic pipes were mentioned as distinguishing reasons for poorly functioning innovative circular technologies waterpoints.

All e-tags on taps from the concrete tanks function well. The concrete ones were installed in 1972 and are still intact while the plastic ones were first installed in 2011 then immediately broke. They were replaced in 2012 after cracking, then re-installed in 2016.

The foregoing confirmed Lockwood et al. (2003) dimension of technical functionality was an important determinant of sustainability. This dimension speaks to the fact that the integrity of the physical conditions of a water system based on factors such as construction quality, leaks, or defects mattered in determining the overall functionality, and thereby sustainability of an entire freshwater scheme.

In contrast, the issue of non-functioning waterpoints was not found to be a problem in Msowero. Freshwater scheme leaders attributed the successful functionality of meters in Msowero to adequate water pressure and high-quality distribution pipes. Both overhead tanks in Msowero were made of concrete. One of the tanks was 25 m^3, the second was 10 m^3, and the third was 5 m^3. The 25-m^3 and 10-m^3 tanks were rehabilitated, and 5-m^3 tanks were constructed immediately before innovative circular technologies were introduced. Incidental findings pointed to the height and volume of the water tanks, and quality of distribution pipes as important factors contributing to sufficient water pressure to unlock *e-tag* meters. Another was routine O&M of the distribution system was considered important in order to prevent blockage caused by salinity at joints and junctions. All these speak to the importance of technical, managerial, and institutional functionality in achieving sustainability.

The contribution of poor internet connectivity to the technical functionality of innovative circular technologies was equally found to be a contributing factor. Although at *prima facie* one would place more weight on water pressure and the type and quality of overhead tanks as a source of malfunctioning, the study could not completely rule out the contribution of poor internet connectivity. Internet access on mobile phones in Mvumi, where there was a larger proportion of non-functionality, was generally weaker than Msowero. Interviews with technicians indicated that a connectivity survey was conducted where internet modems were tested, and new upgraded ones were installed on the tower of each water station connected with innovative circular technology. The post-test revealed the newly upgraded modems had sufficient internet connectivity to detect *e-tags* and unlock the water meters to release water. This study confirmed internet connection was generally more unstable in Mvumi than Msowero; however, instability in Mvumi was not severe enough to completely shut down a water station.

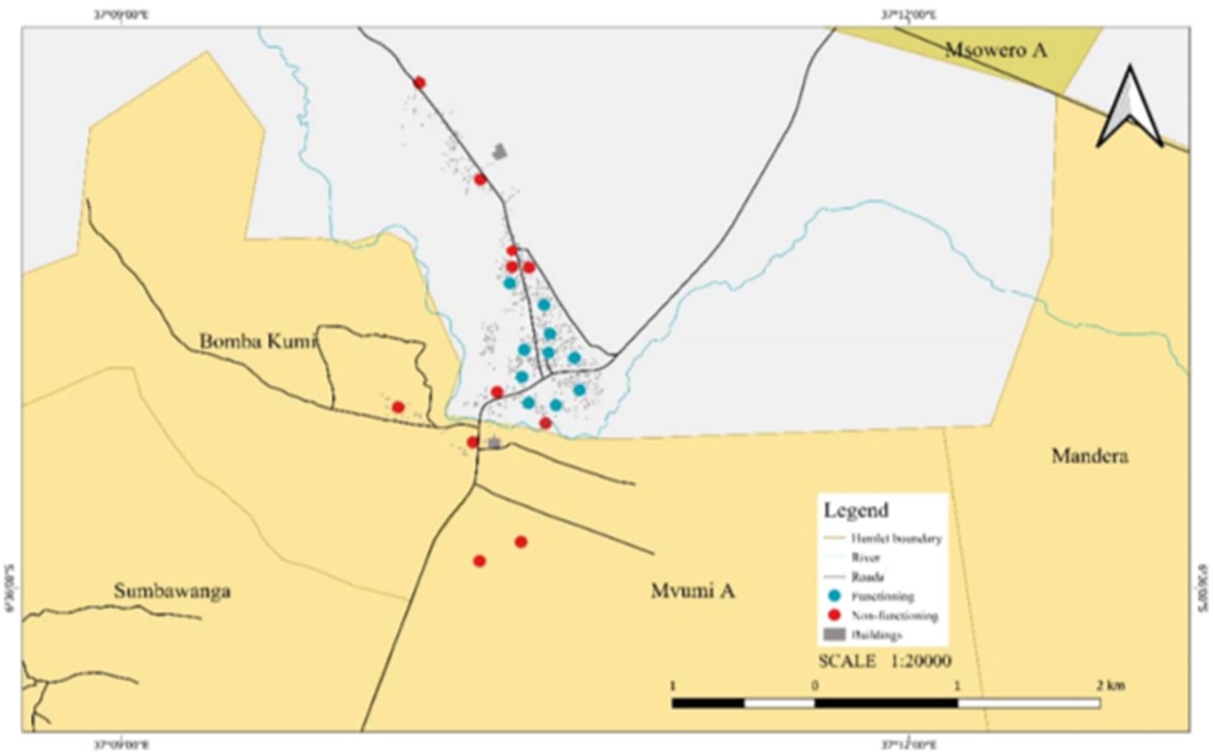


FIGURE 4
Location of malfunctioning water-points in Mvumi.

Nevertheless, there was a strong perception among COWSO leaders that low internet connectivity was the source of non-functionality in Mvumi. This was expressed by the freshwater scheme Chairperson who said, "Maybe a solution to this lies in asking mobile phone companies to also construct a dedicated tower for Mvumi."

Another reason accounting for low pressure in Mvumi was private connections (PCs) in households located in the upstream area of the water scheme. There were 180 PCs in Mvumi. No PCs existed in Msowero, although over 100 applications had already been received at the time of the survey. The study observed PCs received more water because they were located upstream, connected to the big concrete tank, and their taps were located at lower heights compared to community waterpoints. The other factor was that most PCs also stored water in domestic water tanks, which allowed water to flow freely when it started flowing. This was found to cut out water flows to downstream waterpoints connected to innovative circular technologies. However, PCs did not need the same level of pressure to release water as innovative circular technologies did. This meant water would come from PCs and not *e-tag* meters at the same pressure levels. *E-tag* meters were doubly affected because water would be collected by PCs first before reaching *e-tag* waterpoints as the latter were further downstream and needed more time and pressure to be reached. Additionally, PCs were postpaid and often ended up being resellers.

Technical aspects relating to water quality can affect the preservation of natural freshwater sources, thus leading to pollution and waste. It can be seen from Figure 5 that water use from "other sources" was still significant in both case study villages. Other sources were mainly used for washing clothes and bathing in the river in Mvumi.

The persistent use of "other sources" meant community members were still resorting to natural freshwater sources, including fountains and streams. As a result, they ended up contaminating and polluting freshwater from these sources. Conversely, when water was available for domestic use, it tended to be used for activities, which would have otherwise contributed to the pollution of freshwater sources such as bathing (93.3%), washing clothes (84.7%), and drinking water for domestic animals, including livestock (24.4%), in rivers, streams, and fountains. However, the effects of a non-functioning freshwater scheme on circularity can be seen in the case of Mvumi. Mvumi residents used significantly less freshwater for domestic activities than Msowero residents. This was particularly evident in water use for drinking by domestic animals (50.7 percentage points lower), washing clothes (13.5 percentage points lower), and bathing (8.2 percentage points lower).

The implication for this was they were going to "other sources" to fulfill these functions, thus polluting these "other sources" of freshwater, mainly freshwater rivers, streams, tributaries, and springs. This contributed to pollution and the diminishing of river basin-wide freshwater resources. Mvumi was leading in polluting "other sources" by 18.5% through bathing, 16.5% washing clothes, and 3% for drinking for domestic animals including livestock.

The findings show that freshwater schemes made a significant contribution to water circularity and conservation against pollution and contamination of freshwater sources. Figure 6 shows that the proportion of freshwater use in domestic activities increased with the level of functionality of innovative circular technologies in Msowero compared to Mvumi.

It can be seen that there were differences in the proportion of water used for domestic purposes. Only 11% of water users in Mvumi

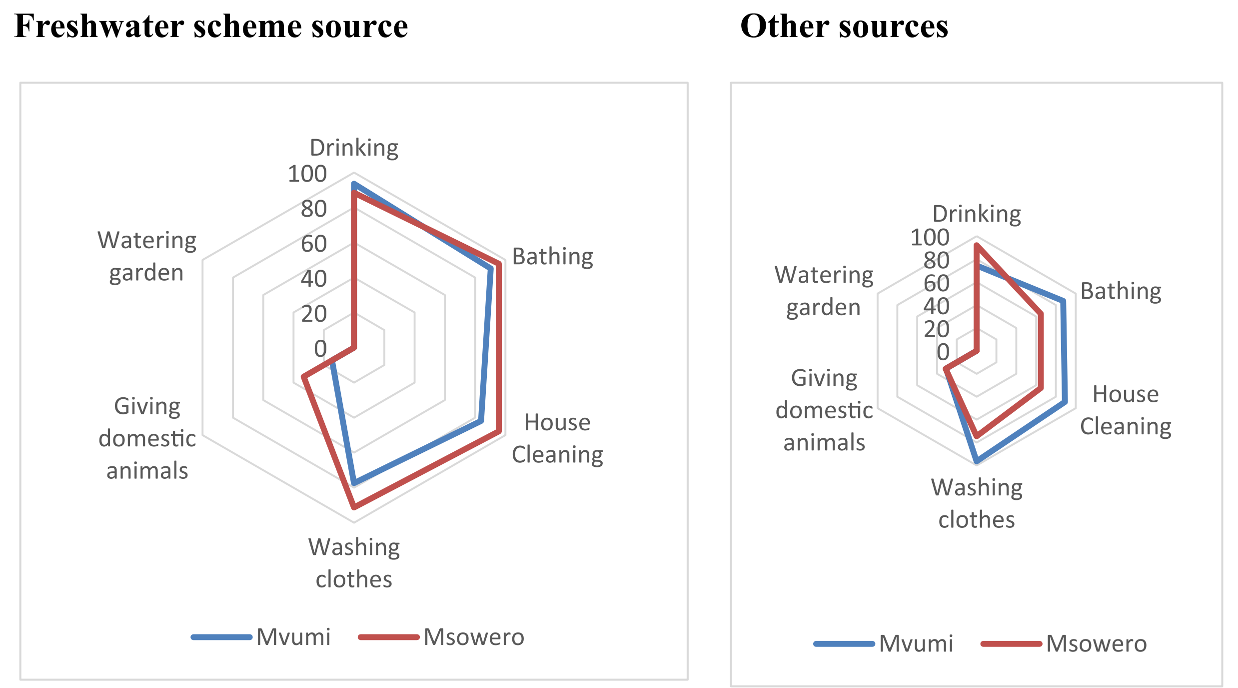


FIGURE 5
Distribution of multiple uses of water among households by source (% of households).

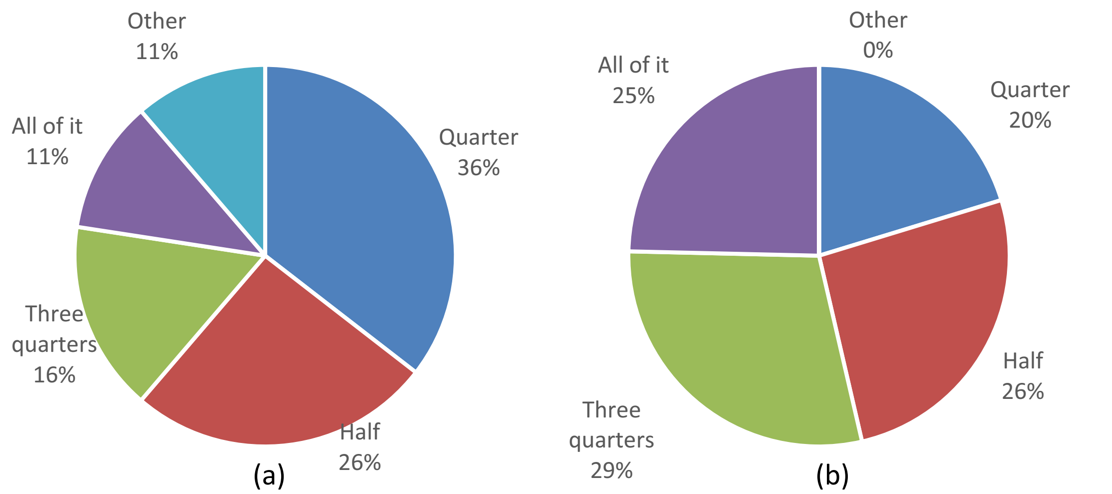


FIGURE 6
Proportion of freshwater from the scheme used in total domestic water use: **(A)** Mvumi and **(B)** Msowero.

used water from the scheme for all their domestic water needs compared to 25% in Msowero. In the same manner, 11% of water users in Mvumi used water from "other sources" compared to 0% in Msowero. The differences reflect a direct relationship between the level of freshwater scheme functionality and water conservation and circularity.

The water circularity principle here was whenever water was drawn from domestic sources, it reduced consumption from sources that could have otherwise been protected. The misuse of these "non-domestic" water resources often led to river basin-wide pollution and the contamination of freshwater sources. By extension, therefore, whenever innovative circular technologies increased the financial and technical sustainability of a water scheme, such as in Msowero, it also contributed to freshwater preservation, conservation, and circularity.

It should be taken into consideration that river water was the traditional source prior to the introduction of water schemes in these river basin catchment community areas. It was therefore customary for water users to resort to this source as the fallback position whenever the freshwater schemes were not functioning. This contributed to the pollution of this important freshwater resource with human and animal waste, wastewater disposal, and multiple uses including bathing and watering livestock.

Consistent with Lockwood et al. (2003), it was found that social factors and culturally induced preferences played an equally important role in diverting users from freshwater scheme utilization. The study reported complaints from water users who treated water from freshwater schemes that had salinity, alkalinity, and varying levels of odor from chlorine used in water treatment. This was evidenced by findings from FGD interviews in Mvumi, where water users expressed that when there was a ceremony in the village, it was normally announced there were two drums of drinking water: one from a freshwater scheme tap and another from a borehole. Most people would opt to drink water from the borehole. This was corroborated by female water users from households who informed the study they did not use water from the freshwater scheme for making tea, cooking, or washing clothes. They also claimed water from the freshwater scheme did not "break" soap easily to produce foam when washing clothes. Water from shallow wells sold by peddlers was a water source of choice for domestic use in Mvumi, even when services from the freshwater scheme were functioning.

Water users suggested that freshwater treatment should be regulated to reduce the strong odor. Both water users and freshwater scheme leaders in Mvumi were of the view that water treatment should be done in smaller daily doses than the present treatment practice. Mvumi was using Aquatabs water treatment solution, which was fixed in a sieve inside water storage tanks and treated water as it passed through. When water service was interrupted along a distribution line, it would remain in contact with the tablets inside the treatment system for some time, causing a relatively strong odor as it repeatedly passed through the sieve unit. Aquatabs is a water purification tablet that contains chlorine dioxide and potassium peroxymonosulfate to disinfect water. Unlike conventional systems relying on coagulation, biotreatment, and sand filtration, Aquatabs are a simple and portable solution. These tablets release chemicals that kill harmful microorganisms, and the process is generally safe and has a low chlorine dioxide dose. The term "relatively high dose" was sometimes confused by water users who perceived a relatively strong odor (which was disliked) with concentration.

While this could have happened sometimes, there was no evidence of a particularly strong odor in tests conducted by tasting and smelling that were randomly conducted during the study.

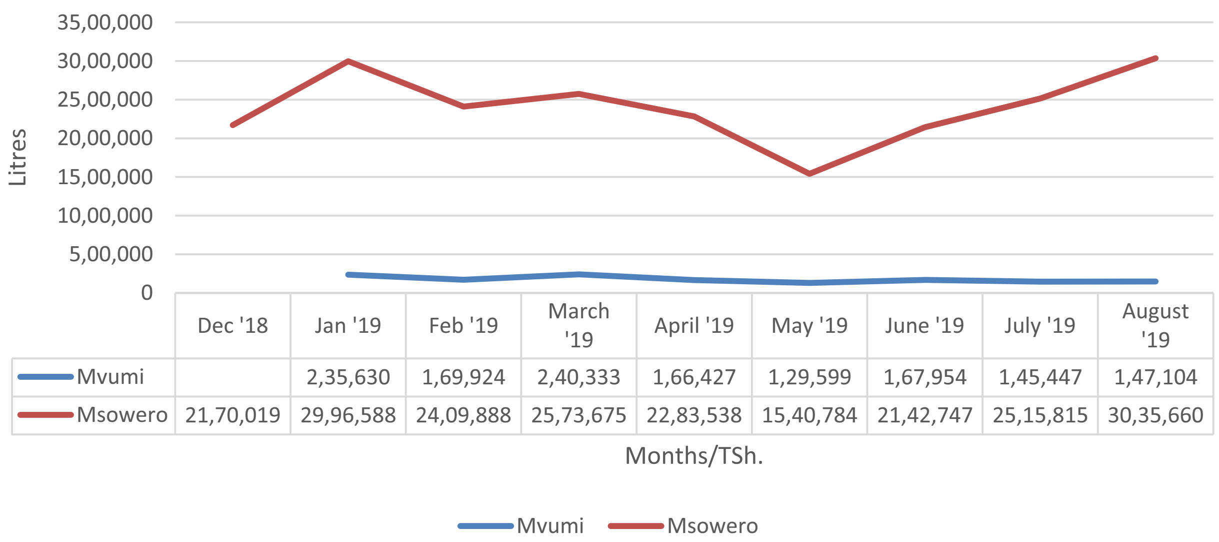
Despite this, the negative perception still affected the uptake of water connected to innovative circular technologies in Mvumi as shown in Figure 7.

Demand-side technical deficiencies also served as a barrier to the sustainability of innovative circular technologies. There was a lot of reselling of *e-tags* by initial subscribers who received them for free during the promotion phase. There was also high reselling from Mvumi to Msowero water users after the initial non-functionality of the system in Mvumi. Water users were found to lack the technical skills to operate innovative circular technologies, leading to a threat to their sustainability.

Most second-hand *e-tag* owners complained that when they recharged their e-tags, they were unable to draw water. According to study findings, 70.9% of water users reported having missed the freshwater supply service because they could not recharge their e-tags. Only a hissing sound was produced without water flowing, but a credit got deducted from their *e-tags* anyway. The main reason behind this was that second-hand owners were not properly informed of the technical requirement to format an *e-tag* so that new information could be added after it had changed phone numbers.

Reduced waiting time was an important criterion for acceptance of water user and long-term sustainability of innovative circular technologies. A combination of low technical skills to be able to redeem water from *e-tags*, long non-functionality periods, inability to unlock the taps due to low pressure, and internet connectivity were sources of dissatisfaction in Mvumi and varying levels of satisfaction in Msowero (see Figure 8).

Even when taps were functional, there were other technical challenges, which served as barriers to the utilization of innovative circular technologies. The system required a water user to first physically go and swipe the *e-tag* at the meter the user was registered



	Dec '18	Jan '19	Feb '19	March '19	April '19	May '19	June '19	July '19	August '19
Mvumi		2,35,630	1,69,924	2,40,333	1,66,427	1,29,599	1,67,954	1,45,447	1,47,104
Msowero	21,70,019	29,96,588	24,09,888	25,73,675	22,83,538	15,40,784	21,42,747	25,15,815	30,35,660

FIGURE 7
Water consumption in Mvumi and Msowero. Source: Service provider's dashboard water operator monthly revenue statement.

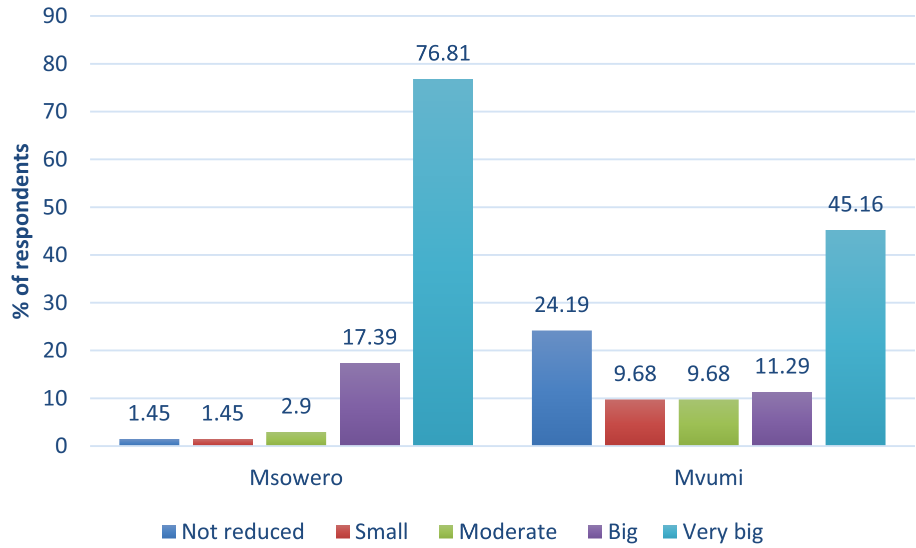


FIGURE 8
Satisfaction of water users with the contribution of innovative circular technologies on the reduction in average time to fetch water.

in order to "redeem" or "transfer" the credit to the *e-tag*. If this was not done, then the *e-tag* would not unlock the water meter. There were generally high levels of dissatisfaction in Mvumi that innovative circular technologies had actually served as a barrier to being able to collect water from metered as opposed to non-metered taps (see Figure 9).

There was high dissatisfaction with the way innovative circular technologies failed to unlock water pipes in Mvumi. Whereas water users could, in principle, access water when community taps were operated under the cash-for-sale system, they could no longer access it because it was "locked up" by the non-functioning innovative circular technologies only to be unlocked by recharging *e-tags*. However, the *e-tags* were not recharging, and when recharged, they were not opening for a number of different technical malfunctioning reasons. This negative attitude was reinforced by the fact that the new scheme was only limited to community pipes and was prepaid, while the water of the old scheme was free in community pipes and postpaid for household connections.

This, water users were left with no option but to return to other, unprotected water sources, thus contributing to pollution. This led to high dissatisfaction among water users, speaking to Lockwood et al. (2003) point that social acceptance was an important dimension of sustainability.

The findings show that the innovative circular technologies adopted to support sustainable circular water management were more successful in delivering water user satisfaction, maintaining functioning waterpoints, and increasing freshwater scheme revenues in Msowero compared to Mvumi. Although innovative circular technologies were first introduced in Mvumi, there were multiple compounding challenges in Mvumi, compared to Msowero. The foregoing challenges contributed to the catastrophic failure of the technologies in Mvumi.

First, Mvumi had more alternative freshwater sources than Msowero. This meant less water user reliance on innovative circular technologies waterpoints.

Second, there was less ownership of the scheme in Mvumi than Msowero. This was primarily because the Mvumi freshwater scheme was formed only after the completion of the construction phase of its physical water infrastructure. The freshwater scheme was not involved in the design of the water scheme, nor had it invested in the construction phase. As a result, it had not fully embraced ownership of the water infrastructure construction phase.

The distribution pipes used to construct the Mvumi freshwater scheme were substandard. They were grade B instead of grade D as required by specifications. As a result, pipes frequently split or broke, leading to leakage and water loss. This contributed to the non-functionality of the innovative circular technology connected to waterpoints in downstream areas.

The tariff setting in Mvumi was also discriminating against those connected to innovative circular technologies. Water from community pipes was more expensive per liter than water from PCs. The rate charged to PCs in Mvumi was TSh. 1.6 per liter compared to TSh. 2.5 per liter from the innovative circular technologies waterpoints. The introduction of innovative circular technologies coincided with an increase in the price of water at public taps, while prices of PCs remained unchanged.

Unlike Msowero, Mvumi had a preexisting water scheme that was constructed in the 1970s, before innovative circular technologies were introduced. Water was once provided free through the old scheme, which was governed under a water policy, which did not require user fees. However, once a new physical infrastructure was constructed, its management shifted under the ambit of the 2002 Water policy, which required user fees. The construction and/or renovation of the physical water infrastructure through financial support from USAID-WARIDI worked in tandem with the introduction of innovative circular technologies, and the introduction of a new tariff structure. This projected an image among some water users that innovative circular technologies were responsible in some way for the changes from a free scheme to a paid one.

The catastrophic failure of the innovative circular technologies in Mvumi was compounded by several factors—had they been timely

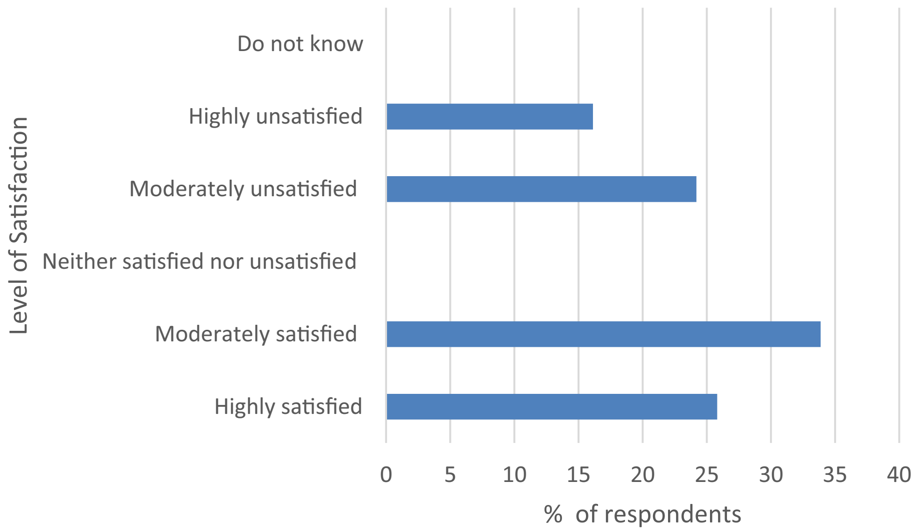


FIGURE 9
Levels of satisfaction on whether innovative circular technologies made it easier to collect water in Mvumi (%).

addressed, the technologies would have successfully gained traction. Community leaders were positively predisposed to embrace the technology in the beginning, but the cascading effect of failures imposed a negative perception, diminishing their expectations. This points to the importance of sociological analysis to inform, educate, and communicate stakeholder involvement at each stage and public relations to sustain public support for innovative circular technologies. These factors, coupled with poor change management during the introduction of the innovative circular technology meters caused potential hostility from certain sections of the community in Mvumi. This resulted in poor community labor contribution during the construction phase as evidenced by several spots of shallow furrows with exposed distribution pipes. As a result, these areas were most vulnerable to ruptures, leakages, and water loss.

5 Discussion

This study clearly shows a strong interrelationship between the different dimensions mentioned by Lockwood et al. (2003). The innovative circular technologies introduced in the case study area were designed to operate E-waterpay meters in order to improve the overall governance and accountability of the collection, management, and reporting of water fees. The design took into account that this would increase financial sustainability, which would increase routine O&M, and therefore the technical and operational dimensions of water schemes.

This premise was supported elsewhere by Ghisellini et al. (2016), who provided examples of how innovative circular technologies have benefitted in promoting circular economy practices in the European Union (EU) including waste-to-energy plants, recycling facilities, industrial symbiosis networks, and significant reductions in waste, energy consumption, and greenhouse gas emissions. In Germany, for example, business models were developed to harness the potential of innovative circular technologies to create new business opportunities including those aimed at stimulating innovation in recycling, repair, and remanufacturing; improving public health outcomes by reducing exposure to hazardous substances; and business opportunities which contributed to more sustainable and equitable communities (Ghisellini et al., 2016; Corral-Verdugo and Steg, 2017). In SSA, innovative circular technologies contributed to increased water efficiency and practices through the early detection of leakages, repair, rainwater harvesting, and wastewater reuse, thereby reducing overall water consumption and associated treatment costs by water utilities (Corral-Verdugo and Steg, 2017; Moyo and Ochieng, 2023). Their deployment in Nigeria contributed to water efficiency and increased revenues by reusing treated wastewater for various purposes such as irrigation and industrial processes, thus creating new revenue streams for water utilities (Ololade and Olaniyi, 2022).

Nevertheless, Moyo and Ochieng (2023) found that the adoption of innovative circular technologies faces several limitations. Their effectiveness is often marred by a lack of technological capacity and supporting infrastructure to implement advanced water treatment and reuse technologies. In their study, Moyo and Ochieng (2023) found that the high initial investment costs of purchasing circular economy technologies made it very difficult to purchase and sustain rural water schemes in Africa. They further raised concerns over their use for wastewater treatment because of their significant energy input, which increases their operational costs and environmental impact (Moyo and Ochieng, 2023).

Agyei-Tetteh and Osei-Kofi (2021) reported that innovative circular technologies were not socially accepted in Ghana when applied to the recycling and purification of wastewater (including from rain and surface water harvesting) and sanitation. Communities intensely disliked treated water due to concerns about their safety and the fact that the technology was foreign-sourced. The main reason cited for this limitation was poor public information, education, and communication (IEC). Additionally, the innovative technologies were negatively appraised for widening social and economic disparities within communities in India. Low-income households struggled to afford the upfront costs, even when they were subsidized. This led to an unequal distribution of water resources and access to services, leading to social tensions and conflict between communities. This made it difficult to implement a freshwater distribution scheme in an equitable and sustainable human economic development manner (Corral-Verdugo and Steg, 2017).

While Grumbach and Hamant (2020) recognize some advancements which humans have made in using technology to provide unprecedented opportunities to conserve and improve the Earth's ecosystems, they argue that they should not be seen as a panacea that can address all limitations of the planet and they only address individual, isolated solutions to address short-term efficiency without prioritizing long-term resilience.

By combining the studies by Lockwood et al. (2003) and Grumbach and Hamant (2020), this publication makes a significant contribution to the evolving field of sustainability theory, particularly in the context of rural freshwater systems in Africa. It highlights the importance of balancing short-term gains with long-term sustainability. It also supports the notion that despite suboptimal conditions which may be observed in the short term, prioritizing cooperation and interdependence can achieve optimality and foster ecological wellbeing.

This publication contributes the 13-point sustainability checklist provided below based on observations, best- and worst-case scenarios, and an empirical analysis of the findings. Awinia (2019) 13-point sustainability checklist for innovative circular technologies in rural freshwater schemes in Africa includes the following:

i Infrastructure Condition: Assess the physical state of freshwater infrastructure, including pipes, tanks, and alert systems.
ii Immediate Reduction of Water Loss: Immediately attend to water loss arising from leaks and inefficiencies in the distribution system to maintain the required water pressure for all users.
iii Water Pressure: Ensure adequate water pressure is available for all users.
iv Storage Capacity: Evaluate the size, height, and location of overhead tanks to achieve the required water pressure for all users.
v Procurement and Handling: Verify the quality of procured infrastructure and its proper handling during installation to avoid punctures and ruptures.
vi Installation Standards: Adhere to recommended depth and alignment guidelines during ground pipe laying.
vii Internet Connectivity: Assess internet connectivity for smart meter functionality and consider alternative solutions for low-connectivity areas.
viii Operation and Maintenance: Implement robust O&M practices, including regular inspections, repairs, and salinity removal around the pipe joints.
ix Infrastructure Integration: Harmonize old and new infrastructure for efficient water delivery across the entire water distribution system.
x Tariff Structure: Ensure a fair tariff structure and facilitate the transition of all users to prepaid metering.
xi Source Shift: Assess the proportion of water users who shift from unprotected sources to the freshwater scheme.
xii Social Acceptance: Gauge public acceptance of water quality, quantity, and pricing.
xiii Institutional Capacity: Constantly evaluate the ability of the water scheme to address the above sustainability challenges.

This 13-point sustainability checklist provides a simple, empirically supported scorecard for evaluating the performance and sustainability of rural freshwater schemes. It emphasizes infrastructure conditions, water loss, pressure, storage, procurement, installation, connectivity, maintenance, social acceptance, and institutional capacity. The checklist is expected to aid the sustainability management of freshwater schemes and the identification of areas for improvement while optimizing water delivery and ensuring the long-term viability of innovative circular technologies.

This study provides various lessons about how freshwater schemes manage the integration of innovative circular technologies for water conservation and circularity. Social concerns were an important aspect that needed to be integrated into the management of water schemes (World Bank, 2021a; World Bank, 2021b; Moyo and Ochieng, 2023; Ferrovial, 2024). COWSOs need to take a more nuanced approach that balances economic, technical, and social considerations in their sustainability management. Freshwater schemes need to shift their focus from the management of corporate affairs to the management of a governance framework that takes into account the needs of all stakeholders, social needs, demands created by new technologies, and institutional capacity.

Sustainability checklist by Lockwood et al. (2003) is, however, not without limitations. The checklist is very specific for assessing the sustainability of rural water supply and is not easily applied to all types of rural water supply, particularly those in more challenging environments needing sustainability analysis. In addition, the checklist provides only eight dimensions and overlooks their interrelationships. Some dimensions such as community, social, satisfaction, willingness, and choice are difficult to measure empirically in an objective analysis. The checklist does not have specific metrics or indicators to measure sustainability performance. Moreover, some of the dimensions overlap, making it difficult to isolate their contributions.

These limitations have motivated other scholars to develop guidelines, which are suited for more complex, interrelated, and challenging environmental conditions, as well as resource use. Grumbach and Hamant (2020) developed guidelines to assess how humans can coexist with the Earth under conditions of suboptimal systems. They argued that by understanding and embracing suboptimal systems, people can better navigate the complex challenges of human–Earth coexistence. They emphasized that sustainability analysis should focus on resilience, which is a system's ability to withstand disturbances and maintain its essential functions under the circumstances of suboptimality where a system operates less efficiently than it could theoretically. Grumbach and Hamant (2020) contended that suboptimal systems can be more resilient precisely due to their redundancy, diversity, and flexibility. These characteristics enable them to withstand shocks, adapt to changing conditions, and respond to unexpected challenges. They further proposed that attention should be given to the relationship between three interrelated systems, namely biological, technological, and sociocultural systems.

Their sustainability analysis starts with the premise that the human immune system, while not perfectly efficient, is resilient due to its ability to adapt to a wide range of pathogens through its exposure to them. Similarly, more decentralized natural resource management streams can be more resilient to disruptions than centralized ones. In the sociocultural realm, suboptimal rules and institutions can help maintain social cohesion and stability.

Checklist by Grumbach and Hamant (2020) offers a way to balance suboptimality in resource use and emerging challenges. It offers avenues to accommodate tradeoffs, including the tension between short-term efficiency and long-term resilience, the conflict between individual and collective interests, and balance between uncertainty and control. It can therefore be deduced that a sustainability checklist based on the checklist by Grumbach and Hamant (2020) would have the following five dimensions:

i System assessment

- Heterogeneity: The system exhibits diversity in its components and processes.
- Redundancy: There are multiple ways to achieve the same goal within the system.
- Slowness: The system has built-in delays or buffers that allow for adaptation.
- Randomness: The system contains elements of unpredictability or chance that contribute to resilience.
- Interdependencies: The relationships between different components of the system are complex.

ii Human–ecosystem interactions

- Impact assessment: The impacts of human activities on the ecosystem are regularly assessed and monitored.
- Mitigation strategies: Effective strategies are put in place to mitigate negative impacts and promote ecosystem health.
- Long-term consequences: The potential long-term consequences of human actions are considered in decision-making.

iii Technological innovation

- Sustainability focus: Technological advancements are developed with sustainability in mind.
- Ethical considerations: Ethical implications of new technologies are carefully evaluated.
- Balance with nature: Technologies are used to enhance human–nature interactions without compromising ecosystem integrity.

iv Socioeconomic systems

- Optimization vs. resilience: Socioeconomic systems prioritize resilience over short-term optimization.
- Collective interests: Decisions are made that consider the long-term interests of individuals and society as a whole.
- Suboptimality adoption: Strategies are put in place to embrace suboptimal practices that may promote resilience.

v Planetary-scale resilience

- Global perspective: Decisions are made from a global perspective, considering the interconnectedness of different ecosystems and societies.
- Collaborative efforts: International collaborations are developed to address global sustainability challenges.
- Long-term planning: Long-term plans are developed to ensure the resilience of the planet for future generations.

6 Conclusion and recommendations

The study identified problems related to the adoption of innovative circular technologies in rural freshwater supply. Innovative circular technologies increased financial sustainability by improving financial management and control. The technology used Internet-powered mobile phone technology to collect and transfer water fees directly from water users to an *e-tag*. It then transferred the fees to a dashboard and, finally, to the bank. Using eight-point checklist of sustainability by Lockwood et al. (2003), this study found that factors which mitigate the sustainability of innovative circular technologies can come from unexpected sources. The case study showed that institutional and management factors were the main source of the non-functionality of circular technologies.

The foregoing is typical in rural Africa, where projects are done in pieces. This usually results in incompatibility between parts, leading to system-wide failures. This was demonstrated by the study findings which showed the construction of the freshwater scheme was done in phases over the years, leading to the non-functionality of innovative circular technologies. This study underscores the need to take into account the overall freshwater scheme architecture and supportive physical infrastructure when designing further extensions downstream.

This study further established that social factors play an important role in the sustainability of innovative circular technologies. In the case study, on the one hand, they generally improved transparency and prospects of financial sustainability, improved water service, and increased confidence among the COWSO leadership in Msowero. However, on the other hand, multiple technical, water service, and financial failures lower expectations and entrenched negative attitudes toward adopting the technology. Sociological factors were important in ensuring equity and fair distribution among all types of water users. For the introduction of innovative circular technologies to be successful, there is a need to carefully steer the course around preexisting social divisions and inequalities.

Catastrophic failure pursuant to the introduction of innovative circular technologies can disable preexisting freshwater schemes, resulting in increased pollution of freshwater sources. Contingency measures need to be put in place so that when failing innovative circular technologies disable waterpoints—either because of low pressure, internet failure, or recharge system functionality—the manual system can be used as a backup.

Catastrophic failure regarding the adoption of innovative circular technologies, especially in Mvumi, does not mean that their use is a *fait accompli*. In cases such as this, a project life cycle approach needs to be followed. This would involve taking stock, learning lessons, and then re-introducing the technology from stage one. A 13-point sustainability checklist is recommended for use when introducing future technology use in freshwater schemes, especially in Africa.

Innovative circular technologies have the potential to add value to water governance as demonstrated in Msowero village. Water users who accessed services from functioning pipes expressed satisfaction with the services. Innovative circular technology reduced the time spent collecting water and extended the time that users could access water daily. However, the functionality of circular technologies depends on the functionality of the overall water physical infrastructure and the functionality of both the demand and supply sides of technical capacity.

Attention needs to be given to multiple dimensions of the sustainability of freshwater schemes. This includes technical, financial, social, cultural, and environmental dimensions of sustainability. Low attention to any of these dimensions is likely to lead to the non-functionality of waterpoints.

There is also a need to consider the community ownership of freshwater schemes right from the beginning. These include social acceptance and community participation. Community ownership will have a positive effect on people's willingness to pay for services, which, in turn, will improve financial sustainability and technical ability to provide ongoing O&M of its physical infrastructure.

Another element that is worth exploring is changes in management, including information, education, and communication (IEC), when introducing innovative smart technologies to support the circular management of freshwater schemes. Proper IEC and comprehensive communication will enable users to adopt new technologies, distill fears, avoid mistakes, and, therefore, increase confidence in them.

Finally, power relations, including in whose hands new technologies are placed and decision-making, must be considered. Mistakes in procurement standards can cause deep-seated functional problems, which could harm the overall long-term sustainability of freshwater schemes.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CA: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. Authors used the Google search engine and Gemini for library and archival research, construction of properly constituted citations in APA style, language editing in some sections, and commanding sequential listing references.

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Supplementary material

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