TYPE Perspective
PUBLISHED 20 June 2025
DOI 10.3389/fenvs.2025.1550738

OPEN ACCESS

EDITED BY
Yuan Li,
Shaanxi Normal University, China

REVIEWED BY
Suzanne C. Walther,
University of San Diego, United States
Nidal Mahmoud,
Birzeit University, Palestine
Cornelius Okello,
University of Bern, Switzerland
Tuwani Malima,
University of Venda, South Africa

*CORRESPONDENCE
Selelo Matimolane,
selelom@vodamail.co.za

†These authors have contributed equally to this work

RECEIVED 24 December 2024
ACCEPTED 09 June 2025
PUBLISHED 20 June 2025

CITATION
Matimolane S and Mathivha FI (2025) Tackling rural water scarcity in South Africa: climate change, governance, and sustainability pathways.
Front. Environ. Sci. 13:1550738.
doi: 10.3389/fenvs.2025.1550738

Tackling rural water scarcity in South Africa: climate change, governance, and sustainability pathways

Selelo Matimolane[1*†] and Fhumulani I. Mathivha[2†]

[1]Equitable Education and Economies, Human Sciences Research Council, Pretoria, South Africa,
[2]Department of Water and Sanitation, University of Limpopo, Sovenga, South Africa

Water scarcity in rural South Africa is an escalating crisis driven by climate change, governance inefficiencies, and socio-economic disparities. This perspective synthesizes secondary data through the Integrated Water Resources Management (IWRM) and Socio-Ecological Systems (SES) frameworks, offering a novel lens that bridges macro-policy failures with micro-community resilience, unlike single-framework analyses. Drawing on existing case studies, including Cape Town's "Day Zero" drought and the Greater Giyani Municipality, we highlight both current advances, such as smart metering, rainwater harvesting, and decentralized purification systems, and persistent vulnerabilities, including erratic rainfall, declining dam levels, and under-resourced infrastructure. The IWRM lens exposes gaps in institutional coordination, policy enforcement, and infrastructure investment that undermine equitable water distribution. The SES perspective reveals how rural communities navigate scarcity through informal networks, traditional knowledge, and local adaptation strategies, but also illustrates the limitations of these responses in the absence of state support. We argue that neither top-down governance nor grassroots innovation alone can achieve water security. Instead, sustainable solutions require hybrid, multi-scalar strategies that align regulatory reforms with community-driven resilience. Future efforts must prioritize adaptive infrastructure, context-sensitive technologies, and inclusive governance frameworks to build climate-resilient and equitable rural water systems. South Africa's experience offers instructive lessons for global water governance, demonstrating the need for holistic, systems-based approaches that integrate technical, social, and institutional dimensions. This perspective contributes to a strategic framing for future policy and research aimed at ensuring long-term water security and sustainability in vulnerable contexts.

KEYWORDS
rural water scarcity, integrated water resources management, socio-ecological systems, water governance, climate change adaptation, community resilience, water access equity

1 Introduction

"Water, water everywhere, but not a drop to drink" (Coleridge, 1887) – this famous line highlights the unfortunate reality for many rural communities in South Africa, and it is an evocative reminder of the importance of accessible, potable water for all communities. Water scarcity is a global crisis affecting millions, with rural areas in developing countries

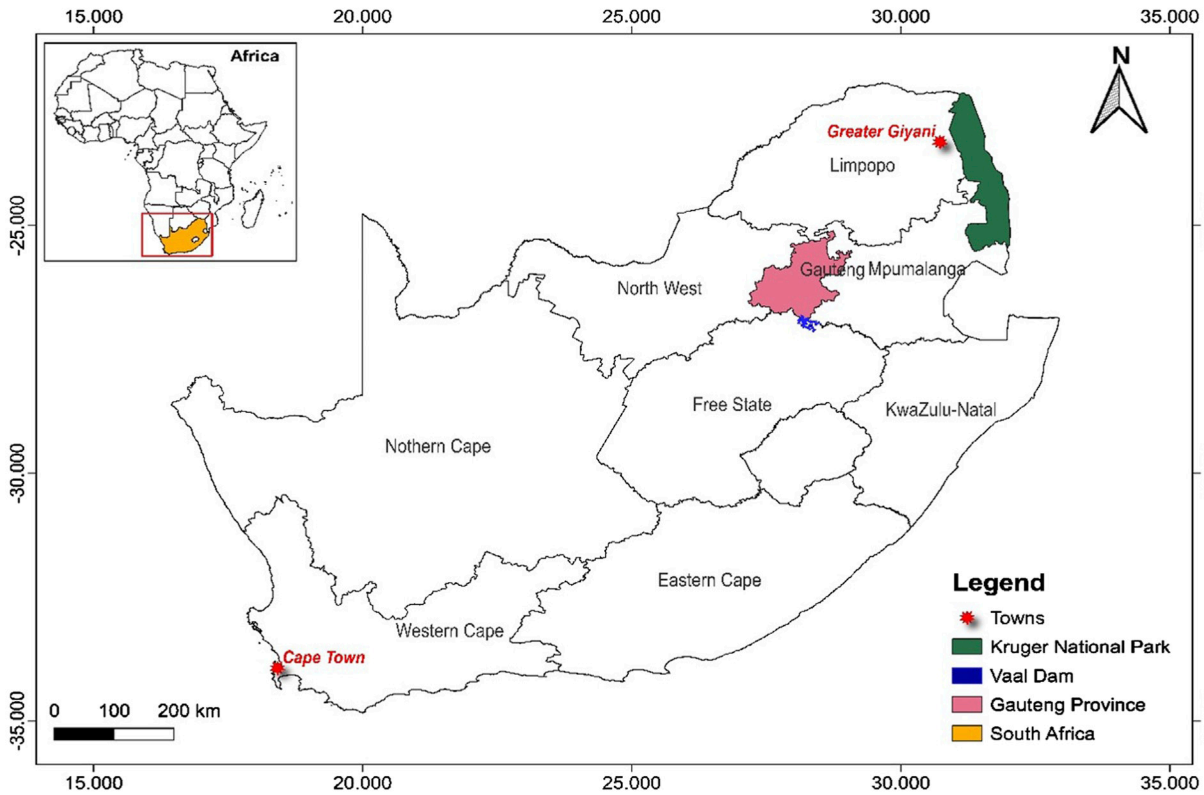

FIGURE 1
Map of South Africa showing the various provinces.

particularly impacted due to lack of clean water, uneven distribution, limited freshwater, pollution, unsustainable use, and inadequate treatment facilities (Emile et al., 2022). South Africa, one of the world's driest nations, faces severe challenges in ensuring reliable access to clean water, especially in rural regions. The issue is so pervasive that access to clean, safe water has become more of a luxury than a basic human right for many communities (Plessis, 2021). South Africa ranks as one of the most water-scarce countries, with an average annual rainfall of only 464 mm/year, much lower than the global average of 860 mm/year (Botai et al., 2016). The United Nations Sustainable Development Goal 6, which emphasizes universal access to clean water and sanitation, underscores the urgency of this issue, yet substantial gaps remain, particularly in rural areas (Hedden and Cilliers, 2014).

Climate change presents an additional complexity for water management in South Africa (Apraku et al., 2023). Increasing temperatures, erratic rainfall patterns, and more frequent and prolonged droughts threaten water availability, especially in rural areas (Baudoin et al., 2017). According to Van Wilgen et al. (2016), the country has seen a temperature increase of about 1.5°C since 196, with projections indicating that the temperature could rise by 4°C by 2100. As climate change affects weather patterns and the hydrological cycle, rural South Africa faces a rising risk of water scarcity, further complicating securing sufficient clean water for its communities (du Plessis, 2019). In 2019, the Department of Water and Sanitation (DWS) reported that over 30% of the country's water resources are already under stress, with South Africa losing 20% of its annual water supply due to pollution and mismanagement (DWS, 2019).

Climate change is expected to exacerbate this challenge, especially in rural communities, where groundwater levels are already low, and droughts are increasingly frequent. In fact, the 2015–2016 drought led to significant reductions in water levels across key dams, such as the Vaal Dam, which is the primary source of water for the Gauteng region, dipping to just 26% of its capacity (Figure 1) (Mathivha et al., 2024; Schreiner et al., 2018). Such events demonstrate the vulnerability of rural communities that depend heavily on surface water for their water needs. Approximately 42% of rural households in South Africa lack consistent access to clean water and rely on unsafe sources like rivers, dams, and unprotected wells (Hedden and Cilliers, 2014). These communities face dire consequences from water contamination, which leads to waterborne diseases such as cholera, typhoid, and dysentery.

South Africa's rural water scarcity is starkly evident in access disparities. The General Statistics South Africa (2023) indicated that while the national average for piped water access is high, only 15% of rural households have piped water inside their homes, and 30% still rely on unsafe or natural sources (unprotected wells, streams, dams, etc.) (see Figure 2). These figures vary significantly by province, with Limpopo and Eastern Cape facing acute challenges due to governance failures and climate impacts Globally, similar patterns emerge in India, where groundwater depletion limits access, and the Sahel, where funding shortages hinder decentralized systems (Jain et al., 2021; United Nations, 2020). Figure 2 illustrates these disparities through an IWRM-SES lens, highlighting policy gaps

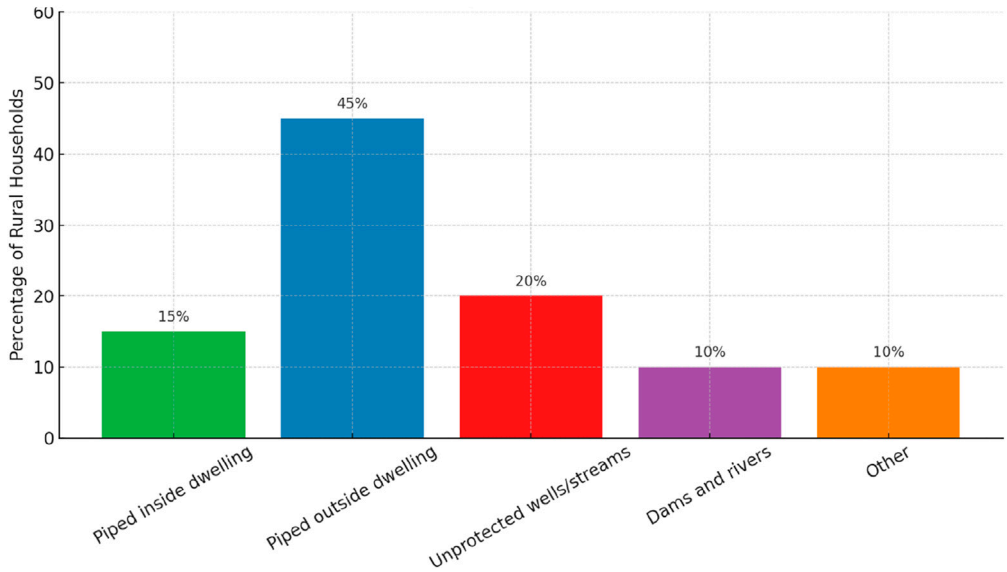

FIGURE 2
Water access Indicators for rural households in South Africa (source: Statistics South Africa, 2023).

and community reliance on unimproved sources, setting the stage for case study analyses.

Despite the country's progressive water policies, such as the National Water Act of 1998, which aims to promote sustainable water use and equitable access, implementation challenges persist, preventing many rural households from securing reliable and clean water. A key factor contributing to this is inadequate infrastructure (Maake and Holtzhausen, 2015). Geographical factors pose another challenge to water access. Many rural regions, especially those in remote or mountainous areas, face difficulties in building the infrastructure necessary to deliver clean water. According to a report by the Water Research Commission (WRC) (2022), the lack of access to proper water infrastructure in rural areas results in higher reliance on unreliable water sources. The Greater Giyani Municipality, for example, has experienced severe challenges in providing water due to the geographic spread and limited transport infrastructure (Bazaanah and Mothapo, 2024). Addressing these challenges requires not only investment in water infrastructure but also the integration of climate adaptation measures, improved governance, and strong community engagement (Mpongwana et al., 2022).

Financial constraints also play a significant role in hindering access to clean water in rural communities. According to a 2017 report by Statistics South Africa (2017), approximately 55.5% of South Africa's rural population lives in poverty, making it difficult for residents to afford private water systems or sanitation solutions. Moreover, government funding for rural water projects is often limited, leaving communities with few resources to address their water needs (Mpongwana et al., 2022). Although the South African government has allocated funds for rural water supply, these resources are often insufficient to meet the growing demands. Consequently, rural communities continue to face major obstacles in securing clean water, leaving many dependent on unsafe, untreated sources that increase their vulnerability to waterborne diseases. South Africa's water scarcity aligns with global challenges in water-stressed regions. In India, groundwater depletion mirrors Limpopo's dam declines, yet community-led watershed management enhances resilience, offering SES lessons for South Africa (Jain et al., 2021). In the Sahel, decentralized water committees, akin to South Africa's Water User Associations, struggle with funding, suggesting shared climate finance strategies (United Nations, 2020). While the Olabanji et al. (2021) and Baudoin et al. (2017) project a 4°C temperature rise by 2100, regional models suggest varied drought severity, necessitating adaptive infrastructure (Ziervogel et al., 2014). Through SES-driven rainwater harvesting, rural communities cope with governance gaps, yet lack formal support, underscoring the need for IWRM-SES integration (Makaya et al., 2020).

South Africa's water crisis cannot be fully understood without accounting for the dual pressures of climate variability and institutional fragmentation. The effects are particularly acute in rural provinces such as Limpopo and the Eastern Cape, where communities rely on vulnerable surface and groundwater systems. For example, the 2015–2016 drought reduced major dam levels to crisis thresholds, exposing both ecological and infrastructural vulnerabilities. At the same time, governance deficiencies have intensified the crisis (Mathivha et al., 2024). Despite progressive legislation like the National Water Act (1998), the country suffers from poor interdepartmental coordination, neglect of infrastructure, and chronic underfunding of rural water systems (Makaya et al., 2020). The failure of large-scale interventions, such as the Giyani Bulk Water Supply Project, reflects deeper systemic weaknesses including overlapping mandates, inconsistent policy execution, and political interference. In many cases, the institutions tasked with delivering water services are under-resourced or ill-equipped to adapt to the growing risks posed by climate change.

2 Analytical framework and approach

In this perspective, we adopt a dual-framework analytical approach that integrates the Integrated Water Resources Management (IWRM) paradigm and Socio-Ecological Systems (SES) theory. This combination provides a holistic lens to interrogate the structural and adaptive dimensions of water scarcity in rural South Africa. It allows us to critically assess institutional constraints, socio-political power dynamics, community coping mechanisms, and the potential of emerging technologies in shaping water outcomes. The IWRM framework, as endorsed by the Global Water Partnership (2000), promotes coordinated development and management of water, land, and related resources to maximize social and economic welfare equitably without compromising ecosystem sustainability (Nkhata, 2020). In the South African context, IWRM is embedded in the National Water Act of 1998, which emphasizes equitable access, efficiency, and sustainability (van Koppen et al., 2011). It also highlights the importance of balancing competing water demands for domestic use, agriculture, and ecological preservation. Applied here, the IWRM lens allows us to examine:

i) Policy coherence between national and municipal levels.
ii) Governance failures, including misaligned mandates, corruption, and poor interdepartmental coordination.
iii) Infrastructure gaps that hinder equitable service delivery.
iv) Regulatory enforcement and institutional accountability, especially in large-scale interventions like the Giyani Bulk Water Project.

The IWRM-SES framework's novelty lies in its multi-scalar integration, unlike resilience theory's focus on system recovery or adaptive governance's emphasis on institutional flexibility. IWRM-SES uniquely combines policy reform with community agency, addressing both structural constraints and local dynamics. For instance, it explains why Giyani's governance failures persist and how Muyexe's harvesting fosters resilience, posing analytical questions like: How do policy gaps exacerbate rural scarcity, and what community strategies mitigate these? This synergy guides case analysis, revealing transferable lessons for urban-rural adaptation.

The SES framework (Ostrom, 2009) provides a complementary perspective by focusing on the interdependence of environmental systems and the human communities embedded within them. It foregrounds issues of adaptability, self-organization, and resilience, key to understanding how rural populations respond to stressors like climate change and infrastructure collapse. Through the SES lens, we examine:

i) Local adaptation strategies, including rainwater harvesting, informal water-sharing networks, and traditional knowledge systems.
ii) Community governance structures, such as Water User Associations and local leadership dynamics.
iii) Social vulnerabilities, including power asymmetries that mediate access to water.

The value of integrating IWRM and SES lies in bridging the top-down and bottom-up dimensions of water governance. IWRM helps explain why well-intentioned policies often fail, due to fragmented institutions, weak enforcement, and political inertia (Enqvist and Ziervogel, 2019). SES, on the other hand, explains how communities survive despite these failures, through locally driven coping and adaptation mechanisms as shown in Figure 3 captures the feedback loops between IWRM's governance nodes (policy coordination, resource allocation) and SES's community loops (adaptation, social networks), illustrating how policy reforms enable local resilience and community actions inform governance (Global Water Partnership, 2000; Ostrom, 2009).

This integrated approach also guided our case selection strategy, favoring cases that reflect: (i) diverse governance arrangements (national programs vs. local projects), contrasting community resilience outcomes (urban vs. rural), and availability of reliable data for cross-case analysis. By weaving these frameworks together, we provide a systems-level understanding of rural water scarcity that accounts for both structural constraints and grassroots innovations. This duality is critical to designing interventions that are not only technically sound but socially grounded and institutionally feasible.

2.1 Case study selection

The selection of case studies, Cape Town's "Day Zero" (2017–2018), Greater Giyani's Bulk Water Supply Project, and Muyexe's Comprehensive Rural Development Programme (CRDP) ensure analytical depth and alignment with the IWRM-SES framework. Four criteria guided selection: contextual diversity, data richness, policy/community relevance, and comparative value. Cape Town, an urban conservation case, showcases IWRM-driven policy success (58% consumption drop) but reveals SES inequities (low-income burdens) (Booysen and Ripunda, 2021). Its urban focus may overemphasize governance, mitigated by rural cases. Giyani, a rural infrastructure failure, highlights coordination gaps and mismanagement, and dealing with its extreme corruption may not represent all projects (Jovanovic et al., 2022). Muyexe's CRDP and rainwater harvesting (40% supply increase) reflect SES resilience but face IWRM policy gaps (maintenance failures) (Mathe, 2018; Matimolane et al., 2024). Its small scale limits scalability, offset by Limpopo's broader adoption. Collectively, these cases span urban-rural and policy-community contexts, supported by peer-reviewed data, enabling IWRM-SES synthesis. Despite their strengths, the selected cases have limitations. Cape Town's urban focus may overemphasize policy success, less applicable to rural contexts with limited infrastructure (Booysen and Ripunda, 2021). Giyani's extreme mismanagement may not represent all rural projects, balanced by Muyexe's community-driven approach (Jovanovic et al., 2022). Muyexe's small scale limits scalability, though Limpopo's broader harvesting adoption mitigates this (Matimolane et al., 2023). These limitations are addressed through cross-case synthesis, ensuring a balanced IWRM-SES analysis.

3 Climate shocks and water system resilience in South Africa

While the broader climate and governance context has been outlined in the Introduction, this section focuses on how specific

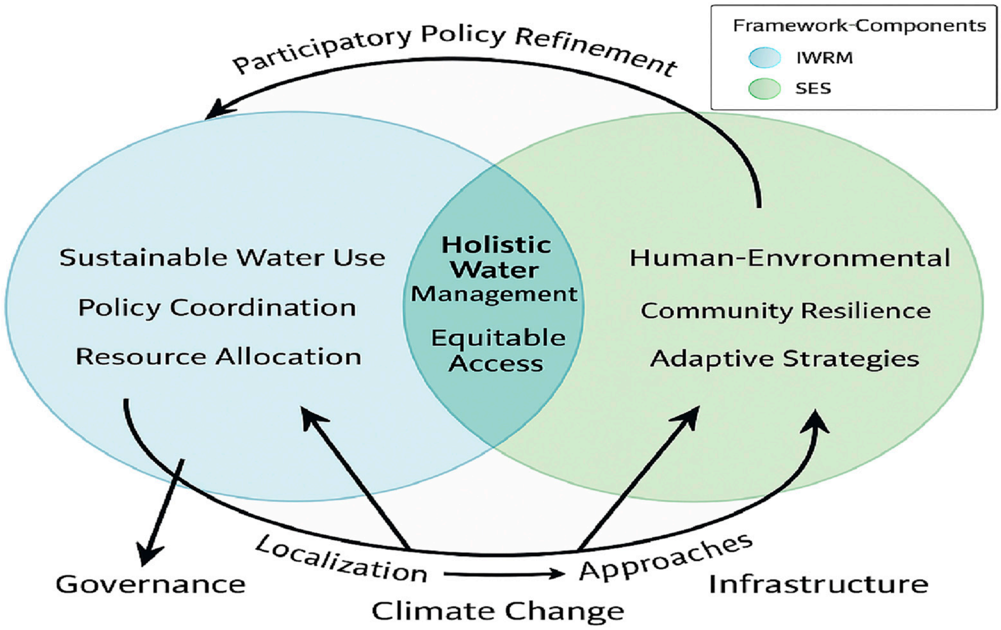

FIGURE 3
Dual framework for analysing water management challenges in rural South Africa.

climate events have tested the resilience of South Africa's water systems. By applying the IWRM and SES frameworks, we explore how prolonged droughts, erratic rainfall, and extreme temperatures have impacted water availability, governance capacity, and community adaptation in both urban and rural contexts. One of the most well-documented examples is the 2017–2018 "Day Zero" crisis in Cape Town, when municipal dam levels dropped below 20%, threatening to cut off water supply to over 4 million residents. In response, the city implemented aggressive demand-side strategies, including daily household limits (50 L per person), public awareness campaigns, and the deployment of smart water meters (Booysen and Ripunda, 2021). These measures succeeded in halving daily water consumption, from 1.2 billion to approximately 500 million liters, but also revealed equity concerns. Wealthier households could afford water storage systems, while lower-income communities endured the most usage restrictions (Calverley and Walther, 2022). From an IWRM perspective, this response showcased effective short-term demand management but lacked long-term structural reform. SES insights further highlight the adaptive capacity of communities but also expose systemic disparities in access to resilience tools.

In rural Limpopo and the Eastern Cape, recurring droughts have severely depleted surface water supplies. Dams such as Nsami and Middle Letaba fell to critical levels during the 2015–2016 and 2019 droughts, disrupting water access for both households and agriculture (Jovanovic et al., 2022). These regions illustrate how low infrastructure redundancy and limited institutional coordination compound climate risks. Governance responses were largely reactive, often relying on temporary water trucking or donor interventions. Through the SES lens, rural communities displayed coping mechanisms, such as rainwater harvesting and informal water-sharing, but these efforts remained constrained without external support. Climate shocks have also affected the agricultural and tourism sectors, which are both water-intensive and economically significant. Farmers in the Free State have increasingly turned to conservation agriculture and drought-resistant crops in response to shifting rainfall patterns, while regions like the Kruger National Park face biodiversity threats due to shrinking waterholes and altered animal migration patterns (Geißler et al., 2024; Mathivha et al., 2017). These impacts underscore the need for anticipatory governance and flexible infrastructure planning. Yet, current frameworks for inter-sectoral coordination remain weak, limiting the ability of national and provincial governments to manage water trade-offs effectively (Makaya et al., 2020).

Giyani's Bulk Water Supply Project, delayed by corruption, project failures forced communities to rely on contaminated rivers, highlighting IWRM governance failures (Makaya et al., 2020). Muyexe's rainwater harvesting increased supply by 40%, but elite control in Water User Associations limited equitable access, reflecting SES power dynamics (Mpongwana et al., 2022). In Cape Town, while restrictions halved consumption, Calverley and Walther (2022) note low-income burdens, though others argue universal limits ensured fairness (Ziervogel et al., 2014). These cases mirror Australia's Murray-Darling Basin, where governance reforms balanced urban-rural needs, suggesting IWRM-SES lessons for South Africa (Alexandra, 2018).

4 Analysis of strategies selected to address the water crisis

4.1 Water conservation and demand management initiatives in South Africa

South Africa has implemented various water conservation and demand management initiatives aimed at promoting sustainable water use, particularly in rural areas. These efforts focus on encouraging communities to adopt water-saving practices and implementing policies that ensure the efficient management of water resources for the future.

One prominent initiative in South Africa is the Water Conservation and Water Demand Management Strategy, adopted by the government in 2004 to promote water-use efficiency in urban and agricultural sectors (Department of Water Affairs and Forestry, 2004). This strategy aims to reduce the demand for water by promoting water-use efficiency, particularly in urban and agricultural sectors. For example, the Western Cape Province has introduced policies to reduce water use in the agricultural sector by promoting the use of drip irrigation systems, which deliver water directly to plant roots, minimizing waste (Visser et al., 2021). Additionally, the city of Cape Town implemented water-saving measures during the 2017–2018 drought, including restrictions on water use, the promotion of water-saving devices, and public awareness campaigns (Beck et al., 2016). While some of these efforts, such as the promotion of efficient irrigation methods, have yielded positive results, they also faced challenges. During the severe 2017–2018 drought, Cape Town implemented aggressive water conservation measures through the "Day Zero" campaign, including strict household water restrictions (50 L per person per day), installation of smart water meters, and mass public awareness campaigns. These efforts achieved remarkable short-term success, reducing the city's daily water consumption from 1.2 billion liters to approximately 500 million liters (Booysen and Ripunda, 2021). However, a critical analysis reveals that the measures disproportionately burden low-income communities, with limited access to alternative water storage solutions such as private boreholes or rainwater tanks (Calverley and Walther, 2022). Wealthier households could adapt more easily, revealing persistent socio-economic inequalities in water access. Although the campaign succeeded in averting catastrophic municipal water failure, it underlined the urgent need for more inclusive and equitable planning in demand management strategies, particularly for vulnerable populations. In contrast, awareness campaigns like Water Wise proved more sustainable in the long term, as they fostered lasting behavioral changes, and a greater public understanding of water conservation needs Calverley and Walther (2022).

4.2 Water treatment and purification programs

Water contamination is another critical issue affecting rural South Africa, where many communities rely on untreated surface water sources (Odiyo et al., 2020). To address this, several water treatment and purification programs have been rolled out. One such program is the Rural Water Supply and Sanitation Program, which focuses on improving access to clean water in rural areas by providing water treatment plants and improving sanitation systems (McDaid et al., 2018). In areas like Limpopo and KwaZulu-Natal, water treatment facilities have been established to purify surface water, making it safe for consumption. The Water Research Commission (2022) has also developed low-cost filtration systems, which are being implemented in rural schools and households, helping to reduce the incidence of waterborne diseases such as cholera and dysentery. In rural Limpopo, the implementation of small-scale water treatment plants and community filtration systems under the Rural Water Supply and Sanitation Program significantly improved public health outcomes, notably reducing cholera and dysentery cases by an estimated 35% between 2016 and 2019 (McDaid et al., 2018). While the technical success of these interventions is evident, their long-term sustainability remains questionable. Many rural treatment facilities suffer from underfunding, inadequate technical support, and insufficient community training, leading to system failures and maintenance backlogs. This points to a critical weakness: without ongoing institutional and financial support, initial infrastructure gains risk rapid deterioration. Thus, while the program demonstrates that decentralized water treatment can improve health outcomes, its success is fragile and contingent on continued investment and capacity-building.

4.3 Community empowerment and participation in water conservation

Empowering local communities to participate in water management is crucial for the sustainability of water resources. In South Africa, several community-driven initiatives have been launched to encourage local participation in water conservation. One example is the Community Water Supply and Sanitation Program in the Free State, where communities are involved in the planning, construction, and maintenance of water supply infrastructure. This approach ensures that the projects are tailored to the specific needs of the community and are more sustainable in the long term (Soares et al., 2024). Educational campaigns have also been crucial in raising awareness about the importance of water conservation. Programs like Water Wise, led by the WRC, educate communities on how to reduce water consumption and adopt water-saving practices. The campaign has reached millions of South Africans, encouraging practices such as fixing leaking taps, using water-efficient appliances, and promoting rainwater harvesting (Filho et al., 2022; Calverley and Walther, 2022).

4.4 The Comprehensive Rural Development Programme

In addition to water conservation initiatives, the South African government has launched several large-scale programs to address broader socio-economic challenges in rural areas. One of the key initiatives is the CRDP, which was launched in 2009. The CRDP prioritizes the needs of rural communities, ranging from clean water and proper sanitation to decent housing and enterprise development support. Muyexe Village in the Greater Giyani Local Municipality, Limpopo, became the first pilot project for the CRDP (Mathe, 2018). This village served as a model for integrating water access with broader development goals. The Comprehensive Rural Development Programme pilot in Muyexe Village aimed to integrate water provision with extensive rural development objectives. The program achieved tangible results: access to clean water improved by over 50%, and the incidence of waterborne diseases fell by 20% within 3 years of implementation (Mathe, 2018). However, a deeper examination reveals systemic challenges. Project evaluations noted delays in infrastructure delivery, inconsistent water supply due to inadequate maintenance, and limited community involvement in decision-making processes. These shortcomings suggest that while the CRDP offers a promising model for holistic rural development, its long-term success depends on embedding stronger participatory mechanisms and ensuring that infrastructure investments are accompanied by robust operation and maintenance systems. Without these, improvements in water access may not be sustained beyond the initial project cycle. Under the CRDP, significant investments were made to improve infrastructure, including the provision of clean water and the construction of sanitation facilities. This program aimed to create more sustainable, water-secure communities by focusing on holistic development that integrates water management with other aspects of rural life, such as housing, education, and healthcare (Mathe, 2018).18).

4.5 Innovative technologies and solutions for sustainable water usage

Innovation in water management technologies has become increasingly important in addressing South Africa's water challenges. One of the most effective solutions has been the implementation of rainwater harvesting systems (Mwenge-Kahinda et al., 2010). In areas such as the Northern Cape, Mpumalanga, and Limpopo Province, rainwater harvesting has become a key strategy for improving water resilience (Matimolane et al., 2023; Judeh et al., 2022). By collecting and storing rainwater, households, and schools can reduce their reliance on municipal water systems, which are often unreliable, particularly during drought periods. The installation of rainwater harvesting tanks has proven to be a cost-effective and sustainable solution for many rural communities (Matimolane et al., 2023). In addition to rainwater harvesting, solar-powered water purification technologies are providing a reliable and sustainable solution for rural communities with limited access to electricity. One example is the use of solar-powered reverse osmosis systems in remote areas of Limpopo and Mpumalanga, which help purify contaminated water and provide clean drinking water to off-grid communities. These technologies offer a long-term solution to water purification challenges while utilizing renewable energy, reducing both environmental and financial costs (UNDP, 2017).

5 Discussion

The interplay between governance failures and community resilience underscores the importance of using both the IWRM and SES frameworks to analyze South Africa's rural water crisis. While IWRM identifies critical gaps in policy implementation and resource distribution, SES provides insight into how local communities navigate these challenges through adaptation and self-organization. In much of rural South Africa, water scarcity stems from a complex interplay of climate variability, governance inefficiencies, and socio-economic disparities (Makaya et al., 2020). While significant progress has been made in policy development, such as the National Water Act (1998), implementation gaps remain a critical barrier to equitable water access (Nkosi et al., 2021; Makaya et al., 2020). These gaps stem from poor intergovernmental coordination, corruption, and inadequate technical capacity at the local level. For example, the failure of the Giyani Bulk Water Supply Project, which remains incomplete despite significant investments, highlights systemic governance failures that leave rural communities vulnerable to water insecurity. South Africa's experience with rural water interventions demonstrates that technical solutions alone are insufficient to ensure sustainable outcomes. Projects that achieved short-term success, such as Cape Town's aggressive water-saving measures and Limpopo's rainwater harvesting programs, did so in contexts where public engagement, local leadership, and sufficient resourcing aligned. In contrast, large-scale infrastructure efforts like the Giyani Bulk Water Supply Project, which remains incomplete despite significant financial investments, illustrate how governance failures, corruption, and weak intergovernmental coordination can derail even well-funded initiatives (Makaya et al., 2020). These contrasting experiences highlight that future strategies must not only emphasize innovative technologies or infrastructure expansion but must also critically address institutional capacity, transparency, and equity to achieve durable water security outcomes. Using the dual lenses of IWRM and SES theory, we discuss and extract key cross-cutting insights that underpin sustainable and equitable water governance in South Africa.

5.1 Policy ambition vs. delivery failure

South Africa's water governance framework is among the most progressive globally, anchored in the constitutional right to water and operationalized through the National Water Act (1998). However, the Giyani Bulk Water Supply Project, despite high-level policy support and substantial public investment, remains a case study of implementation failure. Delays, cost overruns, poor contractor oversight, and bureaucratic inertia reflect the challenges of turning ambitious policies into functioning infrastructure. The IWRM framework emphasizes coordination, accountability, and planning integration, all of which broke down in Giyani. This reflects a broader phenomenon where governance structures remain siloed, with weak vertical alignment between national and local actors and limited cross-sectoral coordination. Water management responsibilities are fragmented across departments, with municipalities often lacking the technical and financial capacity to fulfill their mandates. As a result, service delivery suffers, and projects stall or fail entirely. The lesson is clear: without institutional coherence and capacity at the local level, national water policy goals cannot be realized.

5.2 Resilience from below: the role and limits of community adaptation

In contrast to top-down failures, rural communities have demonstrated remarkable, though often overlooked, resilience in coping with water scarcity. Rainwater harvesting, rotational water-sharing systems, and the use of traditional knowledge networks are widespread in villages like Muyexe. These practices exemplify the SES framework's core principles, adaptation, self-organization, and local knowledge embedded within environmental systems. However, this resilience is often born of necessity rather than empowerment. Communities compensate for the failures of the state, often without institutional support, financial resources, or long-term security. Moreover, community adaptation is not uniformly inclusive. In some cases, local elites dominate water committees, and women and low-income groups are underrepresented in decision-making, reinforcing existing inequalities. These internal governance asymmetries are rarely addressed in formal water policies, which often assume a homogenous and cooperative "community." Therefore, while SES-informed approaches highlight important adaptation pathways, they also caution against romanticizing local resilience in the absence of structural support and accountability mechanisms. Empowerment must be coupled with resourcing and inclusion to make bottom-up governance viable and equitable.

5.3 Technology as enabler, not substitute

The Cape Town "Day Zero" crisis exemplified how data, public communication, and behavioral interventions can reshape water consumption patterns under extreme conditions. Technological tools, such as smart metering, mobile alerts, and AI-driven leak detection, played a significant role in halving water usage during the peak of the crisis (Visser et al., 2021). However, these interventions were easier to deploy in a resource-rich, urban context with strong institutional backing and literate, digitally connected residents. In rural contexts, the promise of smart technologies must be tempered by considerations of local infrastructure, technical capacity, and affordability. Solar-powered purification units, remote sensors, and AI models for predictive maintenance hold real potential, but only if introduced through phased, community-inclusive pilots with training and ongoing support. This is where the IWRM framework must intersect with SES: technology planning must be co-designed with communities and embedded in existing governance and environmental systems. Otherwise, tech-based interventions risk becoming "parachute solutions" that fail to take root.

5.4 Learning loops between urban and rural water governance

Finally, the case studies suggest an untapped opportunity for urban-rural learning loops. The institutional innovations and behavior change strategies used in Cape Town, such as aggressive demand management, could be adapted for use in rural areas, especially in small towns or peri-urban municipalities facing similar drought stress. Conversely, the participatory structures seen in Muyexe's CRDP and traditional water-sharing practices in Limpopo could inform more inclusive and resilient models for urban informal settlements. Currently, these insights remain siloed. National learning platforms are weak, and policy knowledge transfer is slow or non-existent. Institutional structures do not encourage horizontal exchange between municipalities, and donor-funded pilots often operate in isolation. Bridging these divides would require a dedicated mechanism, possibly through the Water Research Commission or SALGA, to facilitate inter-municipal dialogue, peer learning, and cross-scalar innovation diffusion.

5.5 Synthesis: reimagining water governance through dual frameworks

Collectively, these insights point to the need for a hybrid governance model that draws on the strengths of both IWRM and SES. The Integrated Water Resource Management framework provides the institutional scaffolding, laws, roles, resource allocation, and planning tools, while SES reminds us that governance is lived, and shaped by relationships, histories, and community-level dynamics. Neither framework alone is sufficient. But when combined, they offer a more realistic and actionable roadmap for addressing water scarcity, especially in rural South Africa, where formal and informal systems are deeply intertwined.

6 Recommendations: pathways to sustainability, innovative directions for addressing water scarcity

Achieving sustainable rural water security in rural South Africa requires a hybrid approach that integrates IWRM's policy-driven solutions with SES's community-centered strategies. While top-down governance reforms are necessary to enhance infrastructure and regulatory oversight, bottom-up innovations must also be supported to foster local resilience and adaptive capacity. The outlook for sustainable water management in the future is shaped by the growing demand for freshwater, increasing population, climate change, and environmental degradation. While the challenges are immense, there are also significant opportunities to implement strategies and technologies that can promote long-term water sustainability. According to the United Nations, global water demand is projected to increase by 55% by 2050, largely driven by industrial, agricultural, and domestic needs (United Nations, 2020). This increasing demand, combined with climate change and population growth, will put further strain on freshwater resources. Water scarcity in rural South Africa is an escalating crisis driven by climate change, governance inefficiencies, and socio-economic disparities (Hedden and Cilliers, 2014)

Thus, addressing these challenges will require the integration of innovative technologies, strong governance, community participation, and global cooperation. The South African case studies suggest that successful water management requires a hybrid model that marries technical innovation with robust governance and community engagement. Emerging technologies, such as AI-driven water monitoring systems successfully piloted in urban Cape Town, offer promise if adapted to rural contexts with sensitivity to socio-economic disparities. However, technology alone cannot overcome structural governance challenges. Lessons from projects like CRDP highlight the importance of sustained community participation, maintenance funding, and local ownership. Therefore, policy reforms must prioritize capacity-building at municipal and community levels, ensuring that infrastructure and technologies are not only deployed but also maintained and adapted to local realities. Replication efforts elsewhere must critically adapt these lessons rather than blindly transplanting strategies, recognizing that context-specific governance and social dynamics are crucial determinants of success.

6.1 Recalibrate intergovernmental coordination and strengthen accountability

One of the most pressing governance gaps lies in the misalignment between national policy goals and municipal delivery capacity. A dedicated intergovernmental National Rural Water Taskforce, housed within the Department of Water and Sanitation (DWS), should be established to coordinate funding flows, project oversight, and technical standards across spheres of government. The South African Local Government Association (SALGA) and the National Treasury should co-develop performance-based funding mechanisms that reward municipalities for meeting service benchmarks. This reform is highly feasible given existing structures, but it requires political will and moderate administrative investment. Scaling up nationally would involve aligning Municipal Infrastructure Grants (MIGs) with newly established performance metrics.

6.2 Invest in decentralized climate-resilient infrastructure

Rural areas remain underserved by conventional bulk supply systems, which are often high-cost, delay-prone, and maintenance-intensive. Instead, investments should shift toward modular, decentralized infrastructure: solar-powered water purification units, gravity-fed rainwater harvesting, and mobile treatment plants for remote settlements. These systems are not only more cost-effective (averaging 30%–60% less than centralized schemes per household served) (Water Research Commission, 2022), but also quicker to deploy. The Department of Cooperative Governance (COGTA) and the Municipal Infrastructure Support Agency (MISA), in partnership with NGOs and local engineering firms, should pilot community-scale projects in high-risk districts. With proper local training, these technologies are highly scalable across provinces.

6.3 Institutionalize inclusive, community-based water governance

The resilience demonstrated by communities in Muyexe and Limpopo highlights the potential of local governance structures, but also their vulnerabilities. Municipalities should formalize Water User Associations (WUAs) and ward-level water committees through municipal bylaws while ensuring compliance with national standards on gender and youth representation. Traditional councils and civil society organizations (e.g., community trusts, and water cooperatives) should be included in planning dialogues. While relatively low-cost, this reform requires investment in capacity-building and facilitation, especially in linguistically and culturally diverse regions. COGTA and SALGA can coordinate nationwide replication using existing ward-based systems.

6.4 Deploy appropriate technology with built-in capacity development

Smart technologies, such as AI-enabled leak detection, flow monitoring, and predictive analytics for drought response, hold immense potential. However, their effectiveness in rural settings hinges on affordability, simplicity, and local ownership. The DWS Innovation Hub, in collaboration with research institutions like the Council for Scientific and Industrial Research and local universities, should lead co-designed pilot programs that include not only hardware but also technical training and follow-up support. The cost of these systems varies from approximately R37,000 to R92,500 per installation (UNDP, 2017), depending on scale but is recoverable over time through water loss reduction. Scalability is contingent on integrating operations and maintenance costs into municipal budgeting processes and ensuring local repair capacity.

6.5 Embed climate forecasting and early warning systems in municipal planning

The increasing frequency and severity of droughts demand proactive, data-driven governance. Municipalities should embed seasonal forecasting, hydrological stress modeling, and early-warning systems into Integrated Development Plans (IDPs). This requires partnerships with the South African Weather Service, WRC, and provincial disaster management centers, which already possess much of the technical infrastructure. Costs are moderate and primarily involve data access, software integration, and training, well within the reach of national grant instruments. This initiative is highly feasible and should be prioritized in the most water-stressed municipalities, such as those in Limpopo, Eastern Cape, and Northern Cape.

6.6 Mobilize blended finance and climate-aligned investment

Many rural water projects stall due to erratic funding cycles and a lack of long-term capital for maintenance. The National Treasury, in coordination with the DBSA and international partners (e.g., GIZ, Green Climate Fund), should develop blended finance mechanisms that combine public subsidies with concessional loans and private capital. These can support decentralized infrastructure, technology deployment, and ongoing operations. To attract investment, all funded projects should include rigorous monitoring and evaluation frameworks and performance-based disbursements. While high in initial coordination cost, such schemes are scalable through structured portfolios, and pilot projects can begin with donor co-financing.

6.7 Establish a national rural water knowledge and learning platform

Knowledge exchange across municipalities remains fragmented, leading to repeated mistakes and siloed successes. The WRC, in collaboration with SALGA and academic institutions, should establish a national digital platform to house case studies, training toolkits, and lessons learned. This platform would institutionalize horizontal learning, allowing rural areas to benefit from urban innovations (such as Day Zero demand strategies) and vice versa. Development and operational costs are relatively modest but might be a barrier for many municipalities in the country,(estimated at under R9.25 million annually), such a platform requires dedicated personnel and stakeholder buy-in. Once established, this platform can also support cross-regional collaborations and peer mentoring.

6.8 Shared lesson; South Africa as a case study

South Africa's unique socio-economic and environmental challenges position it as a valuable case study for global water management. Like South Africa, rural India faces groundwater depletion, but community-led watershed management has improved resilience (Jain et al., 2021). In the Sahel, decentralized water committees resemble South Africa's Water User Associations but struggle with funding (United Nations, 2020). Thus, the country's experience with Cape Town's "Day Zero" highlights the importance of integrating water conservation, public awareness, and governance reforms during periods of extreme scarcity, all together playing a pivotal role in averting a complete water supply collapse (Enqvist and Ziervogel, 2019; Calverley and Walther, 2022). These lessons can inform water-stressed regions worldwide about the efficacy of coordinated responses and community-driven conservation efforts (Enqvist and Ziervogel, 2019). South Africa's unique socio-economic and environmental challenges position it as a valuable case study for global water management. Cape Town's "Day Zero" highlights the efficacy of integrating conservation, awareness, and governance reforms to avert supply collapse (Enqvist and Ziervogel, 2019). The National Water Act (1998) demonstrates progressive governance, emphasizing equitable access and sustainability, and adaptability globally (Schreiner, 2013). By leveraging technologies and crisis management, South Africa can lead in climate-resilient water systems, informing regions like India and the Sahel (Olley et al., 2024).

Despite challenges in implementation and reform, the act emphasizes equitable access, sustainable use, and ecosystem protection, principles that can be adapted globally (Olley et al., 2024). By adopting emerging technologies and building on its experiences, South Africa has the opportunity to lead in developing climate-resilient and inclusive water management systems. These innovations, combined with proactive crisis management strategies, can serve as a model for regional and global efforts to tackle the interconnected challenges of water scarcity, governance, and climate change.

7 Concluding remarks

This perspective has argued that addressing rural water scarcity in South Africa requires an integrated, multi-scalar governance model that reconciles the structural logic of IWRM with the adaptive, localized insights of the SES theory. By examining diverse case studies, Cape Town's Day Zero campaign, the Giyani Bulk Water Supply Project, and the Muyexe Comprehensive Rural Development Programme, we demonstrated how both top-down institutional failures and bottom-up adaptive responses shape water outcomes across rural and peri-urban landscapes. The core contribution of this work lies in its framework-driven synthesis. The IWRM framework provides a lens to critique systemic inefficiencies: misaligned mandates, funding gaps, regulatory breakdowns, and siloed institutional processes. The SES theory, in contrast, reveals how communities mobilize traditional knowledge, social networks, and informal governance mechanisms to survive in the absence of reliable state support. When used in tandem, these frameworks illuminate the tensions and opportunities between formal water policy and lived realities, highlighting both systemic constraints and pathways for transformation.

This perspective does not claim to present new empirical data; rather, it offers a thematic integration and analytical reframing of existing evidence. It responds to the growing need for cross-framework approaches to diagnose governance complexity and inform more socially responsive water interventions. The recommendations, ranging from decentralized infrastructure and climate forecasting to AI-enabled monitoring and participatory governance, are grounded in this dual-framework logic and tailored to South Africa's institutional and ecological realities. Future research should test these propositions empirically by exploring the conditions under which community-based governance models succeed or fail, the political economy of rural infrastructure financing, and the scalability of technological innovations in off-grid environments. In particular, there is a need for interdisciplinary fieldwork that engages both policymakers and rural communities to co-produce knowledge around sustainable water futures. Such research would provide critical insights for operationalizing the hybrid governance pathways outlined in this paper and for strengthening the resilience of water systems in the face of accelerating climate change.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SM: Conceptualization, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review and editing. FM: Conceptualization, Investigation, Methodology, Validation, Writing – original draft, Writing – review and editing, Formal Analysis.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

The authors declare 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 no Generative AI was used in the creation of this manuscript.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Alexandra, J. (2018). Evolving governance and contested water reforms in Australia's Murray Darling Basin. *Water* 10 (2), 113. doi:10.3390/w10020113

Apraku, A., Gyampoh, B., Morton, J., and Karikari, A. (2023). Water security in rural Eastern Cape, SA: interrogating the impacts of politics and climate change. *Sci. Afr.* 19, e01493. doi:10.1016/j.sciaf.2022.e01493

Baudoin, M. A., Vogel, C., Nortje, K. A., and Naik, M. (2017). Living with drought in South Africa: lessons learnt from the recent El Niño drought period. *Int. J. Disaster Risk Reduct.* 23, 128–137. doi:10.1016/j.ijdrr.2017.05.005

Bazaanah, P., and Mothapo, R. A. (2024). Sustainability of drinking water and sanitation delivery systems in rural communities of the Lepelle Nkumpi Local Municipality, South Africa. *Environ. Dev. Sustain.* 26, 14223–14255. doi:10.1007/s10668-023-03190-4

Beck, T. L., Rodina, E., Luker, L., and Harris, L. (2016). Institutional and policy mapping of the water sector in South Africa. *Inst. Resour. Environ. Sustain*. Vancouver, BC: The University of British Columbia. Available online at: https://edges.sites.olt.ubc.ca/files/2016/12/Institutional-Map-of-SA-Water-Sector-Final.pdf.

Booysen, M. J., and Ripunda, C. (2021). When usage matters: time-of-use analysis of Cape Town's Day Zero drought response. *Water Sci. and Technol.* 84 (10–11), 3122–3131. doi:10.2166/wst.2021.324

Botai, C. M., Botai, J. O., Dlamini, L. C., Zwane, N. S., and Phaduli, E. (2016). Characteristics of droughts in South Africa: a case study of free state and north west provinces. *Water* 8 (10), 439. doi:10.3390/w8100439

Calverley, C. M., and Walther, S. C. (2022). Drought, water management, and social equity: analyzing Cape Town, South Africa's water crisis. *Front. Water* 4. doi:10.3389/frwa.2022.910149

Coleridge, S. T. (1887). The rime of the ancient mariner. Library of Congress.

Department of Water Affairs and Forestry (2004). *National water conservation and water demand management strategy*. Pretoria: Department of Water Affairs and Forestry.

Department of Water and Sanitation (2019). South Africa's water resources: status report. Available online at: https://www.dws.gov.za/Projects/National%20State%20of%20Water%20Report/Documents/Final%20Reviewed%20NSoW%20Report%202019-20_approved.pdf.

Du Plessis, A. (2019). "Water as an inescapable risk: current water availability, quality, and risks with a specific focus on South Africa," in *Transforming water management in South Africa: designing and implementing a new policy framework*. Editors B. Schreiner, and R. Hassan (Springer), 1–17. doi:10.1007/978-3-030-03186-2

Emile, R., Clammer, J. R., Jayaswal, P., and others (2022). Addressing water scarcity in developing country contexts: a socio-cultural approach. *Humanit. Soc. Sci. Commun.* 9, 144. doi:10.1057/s41599-022-01140-5

Enqvist, J. P., and Ziervogel, G. (2019). Water governance and justice in Cape Town: an overview. *WIREs Water* 6 (4). doi:10.1002/wat2.1354

Filho, W. L., Totin, E., Franke, J. A., Andrew, S. M., Abubakar, I. R., Azadi, H., et al. (2022). Understanding responses to climate-related water scarcity in Africa. *Sci. Total Environ.* 806 (Pt 1), 150420. doi:10.1016/j.scitotenv.2021.150420

Geißler, K., Blaum, N., von Maltitz, G. P., Smith, T., Bookhagen, B., Wanke, H., et al. (2024). "Biodiversity and ecosystem functions in southern African savanna rangelands: threats, impacts and solutions," in *Sustainability of southern African ecosystems under global change*. Editors G. P. von Maltitz, E. Archer, J. B. Blackie, C. M. Breen, J. Gambiza, J. I. Hoffman, et al. (Springer), 413–450. doi:10.1007/978-3-031-10948-5_15

Global Water Partnership (2000). Integrated water resources management. Available online at: https://www.gwp.org/globalassets/global/toolbox/publications/background-papers/04-integrated-water-resources-management-2000-english.pdf.

Hedden, S., and Cilliers, J. (2014). Parched prospects–The emerging water crisis in South Africa. *Institute for Security Studies Papers* (11), 16. doi:10.2139/ssrn.2690124

Jain, M., Shah, P., and Dhakad, S. (2021). Community-led watershed management for sustainable groundwater use in India. *Water Policy* 23 (3), 567–583. doi:10.2166/wp.2021.045

Jovanovic, N., Willoughby, A., Mpambo, M., Phasha, K., and Rikhotso, Z. (2022). Feasibility assessment and sustainability evaluation of water supply options for implementation in drought affected areas of Giyani: enabling resilience to climate change. *Water Res. Comm.* Available online at: https://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/3039.pdf

Judeh, T., Shahrour, I., and Comair, F. (2022). Smart rainwater harvesting for sustainable potable water supply in arid and semi-arid areas. *Sustainability* 14 (15), Article 9271. doi:10.3390/su14159271

Maake, M. T., and Holtzhausen, N. (2015). Infrastructure and access to water in rural South Africa: a critical analysis. *J. Rural Dev.* 12 (4), 95–107.

Makaya, E., Rohse, M., Day, R., Vogel, C., Mehta, L., McEwen, L., et al. (2020). Water governance challenges in rural South Africa: exploring institutional coordination in drought management. *Water Policy* 22 (4), 519–540. doi:10.2166/wp.2020.234

Mathe, N. (2018). The comprehensive rural development Programme in Limpopo: a case study of Muyexe village. *J. Rural Dev. Stud.* 11 (2), 45–60.

Mathivha, F., Tshipala, N., and Nkuna, Z. (2017). The relationship between drought and tourist arrivals: a case study of Kruger National Park, South Africa. *Jàmbá J. Disaster Risk Stud.* 9 (1), 471–478. doi:10.4102/jamba.v9i1.471

Mathivha, F. I., Mabala, L., Matimolane, S., and Mbatha, N. (2024). El niño-induced drought impacts on reservoir water resources in South Africa. *Atmosphere* 15 (3), 249. doi:10.3390/atmos15030249

Matimolane, S., Selane, L., and Mathivha, F. I. (2024). "Exploring water supply challenges to selected villages of greater Giyani municipality in Limpopo province, South Africa," in *Journal of asian and african studies*. London, United Kingdom: Advance online publication. SAGE Publications Ltd. doi:10.1177/00219096241303946

Matimolane, S., Strydom, S., Mathivha, F. I., and Chikoore, H. (2023). Determinants of rainwater harvesting practices in rural communities of Limpopo Province, South Africa. *Water Sci.* 37 (1), 276–289. doi:10.1080/23570008.2023.2244784

McDaid, S., Smith, R., and Nkosi, T. (2018). Water treatment and purification in rural South Africa. *South Afr. J. Water Res.* 45 (3), 73–86.

Mpongwana, Z., Shumba, K., and Bracking, S. (2022). Reflections on rural household water insecurity: evidence from goboti and khubvi in the eastern Cape and Limpopo provinces, South Africa. *Afr. J. Inter/Multidisciplinary Stud.* 4 (1), 217–233. doi:10.51415/ajims.v4i1.1032

Mwenge-Kahinda, J., Taigbenu, A. E., and Boroto, R. J. (2010). Domestic rainwater harvesting as an adaptation measure to climate change in South Africa. *Phys. Chem. Earth* 35 (13–14), 742–751. doi:10.1016/j.pce.2010.07.004

National Water Act (1998). Government Gazette. Pretoria: Government Printer. Available online at: https://www.gov.za/sites/default/files/gcis_document/201409/a36-98.pdf.

Nkhata, B. (2020). "Climate change and water resources in Southern Africa: a resilience perspective," in *The Palgrave handbook of climate resilient societies* (Palgrave Macmillan), 1–20. doi:10.1007/978-3-030-32811-5_98-1

Nkosi, M., Mathivha, F. I., and Odiyo, J. O. (2021). Impact of land management on water resources, a South African context. *Sustainability* 13 (2), 701. doi:10.3390/su13020701

Odiyo, J. O., Mathoni, M. M., and Makungo, R. (2020). Health risks and potential sources of contamination of groundwater used by public schools in vhuronga 1, Limpopo province, South Africa. *Int. J. Environ. Res. Public Health* 17 (18), 6912. doi:10.3390/ijerph17186912

Olabanji, M. F., Ndarana, T., and Davis, N. (2021). Impact of Climate Change on Crop Production and Potential Adaptive Measures in the Olifants Catchment, South Africa. *Climate*. 9 (1), 6. doi:10.3390/cli9010006

Olley, J., Cvitanovic, M., Ginige, T., and others (2024). A systematic literature review of sustainable water management in South Africa. *Sustain. Water Resour. Manag.* 10, 162. doi:10.1007/s40899-024-01135-x

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science* 325 (5939), 419–422. doi:10.1126/science.1172133

Plessis, E. (2021). Water sustainability in rural South Africa: addressing the crisis. *J. Environ. Sustain.* 6 (1), 1–14.

Schreiner, B. (2013). Viewpoint—why has the South African National Water Act been so difficult to implement? *Water Altern.* 6 (2), 239–245. Available online at: https://www.water-alternatives.org/index.php/allabs/211-a6-2-8/file.

Schreiner, B., Mungatana, E., and Baleta, H. (2018). *Impacts of drought induced water shortages in South Africa: Economic analysis* (WRC Report). *Water Res. Comm.* Available online at: https://www.wrc.org.za/wp-content/uploads/mdocs/2604%20Vol%201.pdf.

Soares, I., Fernandes, G., and Santos, J. M. R. C. A. (2024). Sustainability in project management practices. *Sustainability* 16 (10), Article 4275. doi:10.3390/su16104275

Statistics South Africa (2017). Poverty trends in South Africa: an examination of absolute poverty between 2006 and 2015. Available online at: https://www.statssa.gov.za/publications/Report-03-10-06/Report-03-10-062015.pdf.

Statistics South Africa (2023). General household survey 2023. Available online at: https://www.statssa.gov.za/?p=12211.

United Nations (2020). *United Nations world water development report 2020: water and climate change*. Paris, France: UNESCO. Available online at: https://unesdoc.unesco.org/ark:/48223/pf0000372985.

van Koppen, B., Schreiner, B., and Fakir, S. (2011). "The political, social and economic context of changing water policy in South Africa post-1994," in *Transforming water management in South Africa: designing and implementing a new policy framework*. Editors B. Schreiner, and R. Hassan (Springer), 1–17. doi:10.1007/978-90-481-9367-7_1

Van Wilgen, N. J., Goodall, V., Holness, S., Chown, S. L., and McGeoch, M. A. (2016). Rising temperatures and changing rainfall patterns in South Africa's national parks. *Int. J. Climatol.* 36 (2), 706–721. doi:10.1002/joc.4377

Visser, M., Booysen, M. J., Brühl, J. M., and Berger, K. J. (2021). Saving water at Cape Town schools by using smart metering and behavioral change. *Water Resour. Econ.* 34, 100175. doi:10.1016/j.wre.2020.100175

Water Research Commission (2022). *A water reclamation and reuse guide for South African municipal engineers* (WRC Project No. C2019/2020-00041). Available online at: https://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/TT%20882%20final%20web.pdf.

Ziervogel, G., New, M., Archer van Garderen, E., Midgley, G., Taylor, A., Hamann, R., et al. (2014). Climate change impacts and adaptation in South Africa. *WIREs Clim. Change* 5 (5), 605–620. doi:10.1002/wcc.295