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Enhancing Sustainable and Resilient Water Infrastructure in South Africa in the Face of Climate Change

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Abstract

In the context of climate change, ensuring the sustainability and resilience of urban water infrastructure in South Africa remains a critical challenge. This study investigates the barriers hindering effective water infrastructure delivery and identifies the factors contributing to inefficiencies. It also evaluates strategies to enhance the resilience and sustainability of water infrastructure projects, focusing on water utility agencies across the country. Key research questions include: What are the barriers to the delivery of sustainable and resilient water infrastructure in South Africa? What strategies can enable the delivery of sustainable and resilient water infrastructure in South Africa? Using survey research, statistical modelling, and case study analysis, the study highlights significant challenges such as ageing infrastructure, poor maintenance, financial constraints, climate change impacts, governance issues, inefficient project management, and water resource scarcity. These challenges were found to stem from four core dimensions: inadequate project management practices, organisational and managerial limitations, operational and maintenance deficiencies, and socio-political factors. In response, the study proposes a five-pronged strategic framework to strengthen water infrastructure delivery. Recommended strategies include upgrading and maintaining ageing systems, improving funding mechanisms and financial oversight, adopting climate-resilient technologies, enhancing project management capacity, and reinforcing governance and accountability structures. Implementing these strategies is essential for ensuring South African cities are better prepared to withstand climate-related disruptions and maintain reliable access to water resources. Ultimately, integrating sustainability and resilience into water infrastructure planning and management is vital for securing long-term water security and supporting urban development under changing environmental conditions.

Keywords

barriers; climate change; resiliency; South Africa; strategies; sustainability; water infrastructure

1. Introduction

Infrastructure is widely recognised as the backbone of socio-economic development, facilitating growth and improving quality of life. Over the past two decades, developing countries such as South Africa, China, India, Vietnam, and Thailand have prioritised significant investments in both physical and digital infrastructure, including transportation, energy, water, housing, and information and communication technology. These efforts aim to stimulate economic progress and deliver substantial social benefits (Calderon & Serven, 2014; World Bank, 2020).

In South Africa, large-scale infrastructure development was at the peak during the 1960s and 1970s, driven by significant public investment that are aimed at establishing efficient systems to support socio-economic growth. Public sector water utility agencies, affiliated with the South African Association of Water Utilities (SAAWU)—a Section 21 company established in March 2001—play a key role in this effort. Formerly known as the South African Association of Water Boards, SAAWU represents and coordinates the interests of state-owned water service providers. Its membership includes nine agencies: Amatola Water, Bloem Water, Magalies Water, Mhlathuze Water, Midvaal Water Company, Lepelle Northern Water, Rand Water, Sedibeng Water, and Umgeni Water.

These agencies are responsible for developing critical infrastructure such as dams, pump stations, pipelines, reservoirs, and water and wastewater treatment works. Their projects follow standard project management practices based on the PMBOK framework, progressing through the phases of initiation, planning, design, execution, and closure. Despite these structured approaches, many agencies encounter challenges in delivering projects on time and have implemented remedial measures to address delays. For instance, Umgeni Water introduced its project management plan in 2012 to improve project execution and ensure consistent delivery. This plan aligns with PMBOK principles and incorporates additional procedures tailored to the agency's specific operational needs (Umgeni Water Project Management Plan, 2012).

However, the country has faced persistent challenges in recent years due to ageing and inadequate infrastructure, which have hindered development in various regions. Recognising the critical link between infrastructure development and economic progress (Chakamera & Alagidede, 2018; Coetzee & Kleynhans, 2017; McGaffin et al., 2019; More & Aye, 2017), the South African government has undertaken extensive efforts since the early 2000s to modernise and expand infrastructure across key sectors, including transportation, energy, and water (Cartwright et al., 2024; Fedderke & Garlick, 2008; Fourie, 2006; Marais, 2013).

Despite these efforts, the delivery of infrastructure projects has been plagued by delays, cost overruns, and inefficiencies. The public sector's infrastructure spending, which exceeded ZAR 2.2 trillion (122 billion USD) between 1998 and 1999 and 2014 and 2015, has not yielded the desired outcomes (National Treasury Budget Review, 2016). For example, large-scale water infrastructure projects have seen a 30% decline in delivery over recent years (Aiyetan & Das, 2021; Naidoo, 2016; Watermeyer & Phillips, 2020). Key challenges include inappropriate procurement practices, inadequate project management capacity, poor stakeholder engagement, and political interference (Watermeyer & Phillips, 2020). These issues highlight the need for improved governance, strategic planning, and innovative management approaches to enhance project delivery.

Water infrastructure, in particular, is under immense pressure due to climate change, population growth, and economic demands. South Africa's water security is increasingly at risk, necessitating a shift towards sustainable and resilient water infrastructure. The integration of frameworks such as the water–energy–food–health (WEF-H) nexus offers an opportunity to address the interdependencies between these critical sectors and promote holistic resource management (Mutanga et al., 2024). Moreover, climate-resilient strategies, such as leveraging nature-based solutions and improving governance structures, are essential to address systemic challenges and ensure long-term sustainability (Cartwright et al., 2024; Vinke-De Kruijf et al., 2024).

Despite significant progress in infrastructure development, the absence of comprehensive legal and institutional frameworks continues to impede effective climate adaptation in South Africa's water infrastructure sector (Odeku & Meyer, 2010). Many local municipalities lack dedicated climate change strategies and insufficient integration between adaptation initiatives and disaster risk reduction plans, resulting in fragmented and ineffective policy implementation (Matikinca et al., 2024). Furthermore, resource management challenges persist, particularly the lack of integrated water management systems and targeted capacity-building initiatives that address the specific needs of both urban and rural communities (Vushe, 2021). Institutional constraints and deep-rooted socioeconomic inequalities contribute to unreliable water systems, especially in sparsely populated or agriculturally intensive regions (Dlamini et al., 2024).

The impacts of climate change—most notably water scarcity—further intensify environmental degradation and heighten social vulnerability. While research highlights the urgent need for tools and strategies to support community-level adaptation (Thorn, 2010), local government responses have largely prioritised physical infrastructure investments, often overlooking the social dimensions of vulnerability and resilience (Matikinca et al., 2024). This reveals a critical research gap: the need for a holistic and balanced approach that integrates technical infrastructure development with broader social and environmental resilience measures.

To address this gap, this study aims to investigate the barriers that hinder the effective delivery of sustainable and resilient water infrastructure in South Africa and identify the underlying factors driving these challenges. Additionally, the study evaluates strategic interventions to deliver sustainable and climate-resilient water infrastructure systems. Accordingly, the research questions proposed for this study are:

> RQ1: What are the barriers to the delivery of sustainable and resilient water infrastructure in South Africa?
>
> RQ2: What strategies can enable the delivery of sustainable and resilient water infrastructure in South Africa?

2. Literature Review

Infrastructure development serves as the backbone of a nation's socio-economic growth, enabling critical functions such as transportation, communication, and access to resources like water and energy (Dithebe et al., 2019; Ngowi et al., 2006). However, these benefits are contingent upon the adequacy and reliability of infrastructure provision (Babbie, 2010). South Africa faces significant challenges in delivering sustainable water infrastructure, compounded by climate change. The following review explores current research findings and identifies gaps in this critical area.

2.1. Impacts of Climate Change on Water Infrastructure

Climate change presents serious challenges to the design, operation, and maintenance of water infrastructure worldwide. Rising sea levels, more frequent extreme weather events, and shifting precipitation patterns increasingly compromise the integrity and performance of water systems. Coastal infrastructure is especially at risk from marine and groundwater inundation, which can bypass conventional defences such as sea walls, necessitating more innovative and adaptive management approaches (Maliva, 2021). Water supply systems are similarly vulnerable; climatic variations influence pipe failure rates, potentially reducing breaks in colder regions but accelerating corrosion in hotter, drier areas—thereby requiring context-specific adaptation strategies (Fan et al., 2023; Żywiec et al., 2024). Infrastructure such as dams, levees, and reservoirs face heightened risks from floods and droughts, underscoring the need for flexible designs and resilient construction materials. Climate-induced water quality deterioration, exacerbated by rising temperatures and altered rainfall, increases pollution risks and operational burdens on treatment systems (Quevauviller, 2010a, 2010b). Consequently, climate projections must be embedded in infrastructure planning, using advanced modelling techniques to anticipate future conditions (Nguyen, 2023; O'Neill, 2010).

In South Africa, one of the world's driest countries, climate change has intensified water scarcity. Prolonged droughts, erratic rainfall, and rising evaporation rates are depleting both surface and groundwater sources, straining infrastructure already operating near or beyond capacity (Mukheibir, 2008; Nhemachena et al., 2020; Thorn, 2010). These pressures are especially acute in rural regions, where competition between agriculture and domestic use is high. Additionally, increased frequency of extreme events such as floods and storms has damaged essential infrastructure—including pipelines, treatment plants, and dams—disrupting water supply and inflating repair and maintenance costs (Schulze, 2011). Urban stormwater systems, often outdated or undersized, are overwhelmed during intense rainfall, compounding water management challenges. Climate variability has also degraded water quality: reduced river flows lead to higher pollutant concentrations, while flood events contaminate supplies, jeopardising public health and increasing treatment demands (Vushe, 2021). Moreover, much of South Africa's water infrastructure is ageing and was not built to withstand current climate extremes, rendering it to maintenance needs, operational inefficiencies, and reduced resilience to future climate variability (Edokpayi et al., 2020, pp. 83–115).

2.2. Sustainability and Resilience of Water Infrastructure

Sustainability and resilience are fundamental concepts in water infrastructure management, as they address both long-term viability and the capacity to withstand and recover from disruptions. Sustainability emphasises the efficient use of resources to meet present needs without compromising the ability of future generations to meet theirs. It involves practices such as rainwater harvesting and graywater recycling to optimise resource use and reduce environmental impact (George-Williams et al., 2024; Lee et al., 2022), as well as life cycle thinking to ensure infrastructure remains functional over time (Mortula et al., 2021). In regions like Sub-Saharan Africa, sustainable water infrastructure must also contend with complex societal, technological, economic, environmental, and political challenges to ensure water availability and quality (George-Williams et al., 2024).

On the other hand, resilience focuses on the robustness of water infrastructure systems—their ability to endure and quickly recover from adverse events such as natural disasters or system failures (Mortula et al., 2021). This includes using innovative engineering solutions and nature-based approaches to adapt to evolving conditions like climate change and population growth (Wallis-Lage & Kisoglu Erdal, 2022). Governance plays a critical role in resilience by establishing policies and frameworks necessary for risk mitigation and effective infrastructure management (Atkinson et al., 2022).

Although often discussed separately, sustainability and resilience are increasingly seen as complementary. Sustainability ensures long-term resource stewardship, while resilience addresses short-term responsiveness to disruptions. When integrated, they form a holistic approach to water infrastructure management, enabling systems that are both robust and adaptable (Chambers et al., 2019). Conceptual models that merge these frameworks aid decision-making by evaluating trade-offs and synergies (Mortula et al., 2021), while performance indicators help quantify and guide system design and planning (Kang et al., 2013). However, integrating these concepts is not without challenges—it demands comprehensive governance frameworks and the alignment of sustainability and resilience goals with existing management practices.

2.3. Barriers to Sustainable and Resilient Water Infrastructure

The lack of integrated policy frameworks remains a critical barrier to addressing climate change impacts on water infrastructure. In South Africa, institutional responsibilities are often fragmented across national, provincial, and local levels, leading to duplication of efforts and gaps in implementation. This fragmentation, coupled with inadequate coordination between climate adaptation and disaster risk reduction strategies, impedes effective, unified responses to emerging climate threats (Odeku & Meyer, 2010). Local municipalities—particularly in rural and under-resourced areas—frequently lack dedicated climate change adaptation strategies, which limits their ability to respond proactively to climate-related risks (Matikinca et al., 2024).

Inadequate funding is another pervasive issue, severely constraining the ability of municipalities to upgrade ageing water infrastructure or expand services to underserved communities. Many South African municipalities struggle with insufficient revenue collection from user tariffs and face restricted access to external funding sources due to low creditworthiness and limited technical capacity (Dithebe et al., 2019). These financial challenges are often compounded by procurement, project planning, and implementation inefficiencies, resulting in delayed delivery and escalating costs.

Moreover, a shortage of technical expertise and operational capacity undermines the ability of local governments and water service authorities to plan, execute, and maintain infrastructure projects effectively. This is especially problematic in historically disadvantaged and rural regions of South Africa, where engineering skills and institutional capacity are limited (Dlamini et al., 2024; Kudumela, 2015).

Finally, social inequities and environmental degradation further complicate the delivery of sustainable and resilient water infrastructure. Marginalised communities—often located in informal settlements or peri-urban areas—frequently lack reliable access to clean water and sanitation. Inadequate stakeholder coordination, weak community engagement, and the exclusion of vulnerable groups from planning processes reduce the effectiveness of resilience-building initiatives (Ruiters & Matji, 2015).

2.4. Strategies for Enhancing Water Infrastructure Resilience

Developing integrated policy frameworks that consider the interdependencies of water, energy, food, and health is increasingly recognised as essential for addressing the complex impacts of climate change. The WEF-H nexus provides a strategic model for aligning sectoral policies and promoting sustainable resource management (Adom et al., 2022; Mathetsa et al., 2022; Mutanga et al., 2024). Such frameworks should explicitly incorporate climate adaptation and disaster risk reduction to enhance systemic resilience (Odoh & Ezealaji, 2024).

Financial constraints remain a significant barrier to implementing climate-resilient infrastructure. Innovative financing mechanisms—including public-private partnerships (PPPs) and international climate funds—have been identified as effective tools for mobilising additional resources for water infrastructure while ensuring cost-effectiveness (Pot, 2023). Further, reforms to municipal revenue systems and improved access to credit can support long-term sustainability. Adaptive management strategies, such as floodwater harvesting, wastewater reuse, and smart water technologies, are also central to building resilience in the water sector by increasing resource efficiency and reducing vulnerabilities (Vushe, 2021). Moreover, infrastructure planning must integrate early warning systems and climate-resilient design standards to mitigate the impacts of extreme weather events (Schulze, 2011).

Capacity building is another critical element. Investing in training for municipal staff and water service authorities can strengthen technical and operational competencies. Focused programmes on climate-resilient planning, implementation, and maintenance are essential (Cagliano et al., 2015). Collaborations with academic institutions and international organisations can further enhance knowledge transfer and promote innovation related to sustainable and resilient water infrastructure. In addition, community engagement in planning and managing water infrastructure enhances social resilience and ensures that adaptation strategies are locally relevant. Empowering communities with tools and knowledge for climate adaptation can help address socioeconomic vulnerabilities (Thorn, 2010). Prioritising equity in infrastructure development is key to achieving inclusive and sustainable outcomes.

Furthermore, blue-green infrastructure (BGI) is increasingly recognised as a nature-based solution that supports sustainable urban development and climate resilience. By integrating natural and semi-natural systems—such as rivers, wetlands, green roofs, and urban forests—BGI delivers vital ecosystem services while enhancing urban resilience. It employs natural processes to mitigate flood risks, improve water quality, and support biodiversity, making it a cornerstone of climate-resilient infrastructure. BGI is particularly effective in urban stormwater management. By increasing permeable surfaces and enhancing rainwater retention, it helps restore disrupted urban hydrological cycles (Afata et al., 2022; Pochodyła et al., 2021). Features like rain gardens, bioswales, and constructed wetlands reduce runoff volumes and peak flow rates (Liao et al., 2017; Wu et al., 2024). Wetlands and swales, for instance, address both flooding and water scarcity, showcasing the multifunctional value of BGI systems (Ahmad & Hassan, 2023). Additionally, BGI supports biodiversity by creating habitats and fostering ecological connectivity, aligning with ecological engineering approaches that enhance infrastructure performance and resilience (Perrelet et al., 2024). Socio-economically, BGI offers cost-effective, lower-maintenance alternatives to grey infrastructure. It promotes social interaction, community cohesion, and public health benefits (Afata et al., 2022; Gündel & Kalaycı Önaç, 2023). Technological advances—including machine learning and smart city tools—further improve BGI design, monitoring, and performance, reinforcing its role in sustainable urban water management (Nagal & Prabhakar, 2025). Thought leaders such as Kongjian Yu emphasise water as central to climate action, advocating for BGI and sponge city models that replicate natural water cycles to manage flooding, enhance water quality, and build urban resilience (Green, 2025). Similarly, de Meulder and Kelly Shannon highlight the role of water urbanism in integrating water-sensitive strategies into urban planning. Their research advocates reviving traditional, water-based practices to foster adaptive and sustainable urban design (de Meulder & Shannon, 2013). Despite its benefits, BGI implementation faces challenges. These include the need for interdisciplinary collaboration, integration of ecological principles into conventional engineering, policy and institutional barriers, funding constraints, and limited public awareness. Nevertheless, the potential of BGI to transform cities and develop sustainable and resilient water infrastructure is widely acknowledged. Continued empirical research and case-based studies are essential to advance its implementation and inform policy (Liao et al., 2017; Perrelet et al., 2024).

The literature thus suggests that the barriers to resilient and sustainable water infrastructure are multifaceted, spanning policy, financial, technical, natural, and social dimensions. Addressing these challenges requires a holistic and context-sensitive approach that integrates innovative financing, adaptive management, capacity building, and community involvement. Cross-sectoral collaboration and aligned policies are critical to enhancing sustainable and resilient water infrastructure. However, it remains necessary to identify and respond to localised, context-specific barriers to support the long-term functionality and equity of water infrastructure systems.

3. Research Methods

The study aimed to identify barriers to water infrastructure project delivery and assess strategic measures to support the development of sustainable and resilient infrastructure in South Africa. To achieve this objective, a survey research methodology was employed. Data collection was carried out through a structured survey, and the analysis was conducted using both descriptive and inferential statistical techniques.

3.1. Data Collection

A stakeholder perception survey was conducted as no structured statistical data was available to evaluate the challenges and influencing factors in water infrastructure project delivery. The survey relied on insights from stakeholders actively involved in the water infrastructure delivery system in South Africa.

To prepare for the survey, a list of stakeholders was compiled based on criteria such as professional engagement, involvement in water-related projects, and relevant education and experience. Stakeholders were selected from the KwaZulu-Natal, Free State, and Eastern Cape provinces of South Africa. These regions were selected for their geographical diversity—KwaZulu-Natal in the east, Free State in the centre, and Eastern Cape in the southeast—as well as the presence of significant water utility agencies, access to ongoing infrastructure projects, and the willingness of potential participants. Given the scale and significance of water infrastructure initiatives in these provinces, they were considered representative of broader national trends. Once the list was finalised, stakeholders were invited to participate via email, telephone, or personal networks. The final sample was based on availability and willingness to participate.

Efforts were made to ensure inclusivity and avoid discrimination based on race, gender, nationality, or age, thereby minimising potential bias in the responses.

The final survey included 145 stakeholders, with 120 valid responses received, yielding a response rate of over 82%, which was considered adequate. The respondents comprised a diverse group of professionals involved in water infrastructure, including project managers, civil and planning engineers, quantity surveyors, environmental project managers, and servitude administrators. The group also included technical staff and civil society professionals such as water quality technologists, hydrologists, geologists, mechanical and electrical engineers, information and communication technology specialists, architects, as well as policy-makers and decision-makers.

A pre-tested questionnaire was used for data collection, containing questions on key challenges, influencing factors, and strategic measures to improve project delivery. Respondents rated their perceptions on a five-point Likert scale (1 = *very low*; 2 = *low*; 3 = *average*, 4 = *high*; 5 = *very high*).

The questionnaire was distributed via email, and responses were collected using the same platform.

3.2. Data Analysis

A quantitative approach was used to analyse the survey data, employing both descriptive and inferential statistical techniques. Prior to analysis, the dataset was examined for missing values and outliers to ensure its validity and reliability. The data, collected on an ordinal scale ranging from 1 to 5, showed no issues related to missing entries, outliers, or inconsistencies. Given the non-normal distribution of the data, a non-parametric test was considered suitable for the analysis. The collected data were analysed using IBM SPSS (version 30).

Barriers and strategies were analysed using metrics such as the perception index (*PI*), standard deviation (*SD*), interquartile range (*IQR*), coefficient of variation (*CoV*), and a one-sample Chi-square test. The PI reflected the average ratings assigned by experts for each barrier and strategy, with a $PI \geq 3$ indicating an average or higher rating. In contrast, a $PI < 3$ suggested a lower-than-acceptable rating. The *SD* measured the consistency of responses, with values ≤ 1.0 signifying high consistency. Similarly, an $IQR \leq 1.0$ and $CoV < 30\%$ indicated a strong consensus among respondents (Geh et al., 2022; von der Gracht, 2012). The non-parametric one-sample Chi-square test was used to determine the statistical significance of the responses, with significance set at $\alpha \leq 0.05$ and $p \leq 0.05$.

4. Results and Discussions

4.1. Profile of Respondents

The demographic characteristics of the respondents are outlined in Table 1, which includes details such as professional roles, years of experience, and involvement in water projects. This information was essential to assess the adequacy and reliability of the responses. As shown in Table 1, the distribution of professional roles ranges from 3.33% (environmental project manager) to 19.17% (other professionals). Key stakeholders such as project managers, contractors, consultants, civil engineers, quantity surveyors, and planning engineers are well-represented, indicating a balanced participation of relevant stakeholders in the survey. The others included professionals such as water quality technologists, hydrologists, geologists, mechanical and electrical engineers, information and communication technologists, architects, policy makers, and decision makers.

A significant portion of the respondents (39.17%) have five to 10 years of professional experience, while over 19.17% have 11 to 15 years of experience. Additionally, 15% of the respondents possess more than 15 years of experience, meaning over 74% of the participants have substantial professional expertise. Furthermore, more than 84% of the respondents reported direct or indirect involvement in water projects, while approximately 16% lacked specific water infrastructure project experience but had relevant expertise in other infrastructure domains. These findings indicate that the respondent pool is diverse and representative, making it suitable for the study.

Table 1. Demographic profile of respondents.

Respondents	Frequency	%
Professional engagement		
Project managers	11	9.17
Civil engineers	10	8.33
Planning engineers	9	7.50
Quantity surveyors	11	9.17
Environmental project manager	4	3.33
Servitude administrators	8	6.67
Technical staff	19	15.83
Contractors	16	13.33
Consultants	9	7.50
Other related professionals	23	19.17
Years of experience		
< 5 years	32	26.67
5–10 years	47	39.17
11–15 years	23	19.17
> 15 years	18	15.00
Participation in water projects		
Directly participated in water projects	64	53.33
Indirect association with water projects	37	30.83
Not associated with water projects, but experience in other infrastructure projects	19	15.83

4.2. Perception of Stakeholders on the Barriers to Sustainable and Resilient Water Infrastructure

The analysis of stakeholder perceptions regarding various barriers (Table 2) reveals that ageing infrastructure and poor maintenance ($PI = 4.17$) are the most significant concerns, with the lowest variability ($IQR = 1.0$, $CoV = 13.3\%$), indicating a strong agreement among respondents. Funding and financial constraints ($PI = 3.89$, $IQR = 1.0$, $CoV = 21.5\%$), inefficiencies in project management ($PI = 3.64$, $IQR = 1.0$, $CoV = 21.6\%$) and water resource scarcity ($PI = 3.62$, $IQR = 1.0$, $CoV = 22.7\%$), technological and innovation barriers

(*PI* = 3.53), emerge as high-level or critical barriers, highlighting the financial limitations that hinder progress. Additionally, environmental degradation (*PI* = 3.12) is perceived as a moderate challenge, reflecting concerns about resource allocation and operational effectiveness.

On the lower end of the scale, governance and management issues (*PI* = 2.98), political and policy barriers (*PI* = 2.85), climate change uncertainties (*PI* = 2.76), and social and community challenges (*PI* = 1.78) are perceived as less significant barriers. However, the high Coefficient of Variation (*CoV* = 47.0%) for social and community challenges suggests considerable disagreement among stakeholders, indicating varying perspectives on the importance of social engagement in addressing these issues.

Further, all barriers have *p*-values <0.001 (Table 2), confirming that the differences in stakeholder perceptions are statistically significant. This suggests that addressing the most critical barriers, such as infrastructure deficiencies, financial constraints, and project management inefficiencies, could lead to meaningful improvements. Meanwhile, the variability in perceptions of social challenges highlights the need for targeted stakeholder engagement to bridge differing viewpoints. Overall, the findings underscore the importance of strategic interventions to enhance infrastructure resilience, financial sustainability, and governance efficiency while considering the diverse perspectives of stakeholders.

Table 2. Perception of stakeholders on the barriers to sustainable and resilient water infrastructure.

Barriers	Perception of stakeholders				
	PI	*SD*	*IQR*	*CoV(%)*	*p*-values
Ageing infrastructure and poor maintenance	4.17	0.555	1.0	13.3	<0.001
Funding and financial constraints	3.89	0.848	1.0	21.5	<0.001
Climate change uncertainties	2.76	1.04	1.0	36.4	<0.001
Governance and management issues	2.98	1.115	2.0	37.4	<0.001
Inefficiencies in project management	3.64	0.786	1.0	21.6	<0.001
Water resource scarcity	3.62	0.822	1.0	22.7	<0.001
Political and policy barriers	2.85	0.885	1.0	31.1	<0.001
Social and community challenges	1.78	0.835	1.0	47.0	<0.001
Technological and innovation barriers	3.53	1.004	1.0	28.5	<0.001
Environmental degradation	3.12	1.014	2.0	32.5	<0.001

4.3. Perception of Stakeholders on the Strategies for Sustainable and Resilient Water Infrastructure

Table 3 presents the perception of stakeholders on the strategies for sustainable and resilient water infrastructure. The analysis of stakeholder perceptions regarding strategies to address key challenges indicates that upgrading and maintaining infrastructure (*PI* = 4.36) is perceived as the most significant (very high) strategy. This suggests a strong consensus on the need for infrastructure improvements, with relatively low variability (*CoV* = 15.1%). Similarly, increasing funding and financial management (*PI* = 3.92) is rated High, highlighting financial sustainability as a crucial factor in overcoming barriers.

Other highly rated strategies include enhancing governance and accountability (*PI* = 3.71). The resilience to extreme weather events (*PI* = 3.25), strengthening project management and capacity building (*PI* = 3.13), and integrating climate-resilient technologies ($PI = 3.06$) fall within the Moderate range, indicating their importance in improving system efficiency and adaptability and reflecting the need for long-term investment in human and technological resource as well as the development of institutional frameworks that support sustained capacity enhancement.

In contrast, policy and regulatory reforms ($PI = 2.82$) are rated Low, suggesting that while governance adjustments are necessary, they are not seen as an immediate priority. Community engagement and awareness ($PI = 2.45$) is the least prioritised strategy, categorised as Very Low, with a high *CoV* (50.2%), indicating significant stakeholder disagreement.

Overall, the findings emphasise that infrastructure development and financial investment are seen as the most effective strategies, while policy changes and community involvement are perceived as less urgent, despite their potential long-term benefits. The statistical significance ($p < 0.001$) across all strategies confirms substantial differences in stakeholder perceptions (Table 3), thus necessitating strategic priorities for effective implementation.

Table 3. Perception of stakeholders on the strategies for sustainable and resilient water infrastructure.

Strategies	Perception of stakeholders				
	PI	*SD*	*IQR*	*CoV(%)*	*p*-values
Upgrading and maintaining infrastructure	4.36	0.658	1.0	15.1	<0.001
Increasing funding and financial management	3.92	0.693	1.0	17.7	<0.001
Integrating climate-resilient technologies	3.06	0.836	0	27.1	<0.001
Strengthening project management and capacity building	3.13	0.826	1.0	26.4	<0.001
Enhancing governance and accountability	3.71	0.691	1.0	18.6	<0.001
Resilience to extreme weather events	3.25	0.781	1.0	24.0	<0.001
Policy and regulatory reforms	2.82	1.108	2.0	39.3	<0.001
Community engagement and awareness	2.45	1.229	2.0	50.2	<0.001

4.4. Discussion

South Africa faces significant challenges in delivering sustainable and resilient water infrastructure, compounded by the effects of climate change, ageing infrastructure, financial limitations, and systemic governance inefficiencies. These barriers are deeply embedded in the country's historical, institutional, and socio-political context, influencing both policy and implementation outcomes.

Ageing infrastructure and poor maintenance emerged as the most pressing barrier. This reflects the deterioration of water systems built decades ago, often without consideration for the intensifying impacts of climate variability. These systems were designed for historical hydrological conditions, not the prolonged droughts and extreme weather events experienced today. Infrastructure degradation leads to operational inefficiencies, water losses, and inflated maintenance costs, especially in municipalities with limited technical capacity and budget (Emily & Muyengwa, 2021; Ruiters & Amadi-Echendu, 2020).

Financial constraints also pose a significant barrier. Many local governments struggle with revenue generation (Ruiters & Amadi-Echendu, 2020) due to limited tax bases, low water tariff collection rates, and poor billing systems. These factors, combined with constrained access to external funding and inefficient procurement practices, result in chronic underinvestment and delays (Dithebe et al., 2019). Additionally, political interference in budgeting and infrastructure planning often diverts funds from priority areas.

Project management inefficiencies and water resource scarcity highlight systemic issues in infrastructure project delivery, such as poor planning, lack of technical expertise, and fragmented coordination among stakeholders. Vushe (2021) underscores the absence of integrated water resource management, which is essential for balancing competing water demands and promoting long-term sustainability.

Barriers related to technology and innovation reflect the reliance on outdated infrastructure that cannot accommodate rapid urbanisation or fluctuating climate patterns. Moreover, limited uptake of smart water technologies is often due to cost, lack of technical skills, and risk aversion in public institutions. Governance and institutional fragmentation remain persistent challenges. Odeku and Meyer (2010) argue that unclear mandates, overlapping responsibilities, and insufficient legal frameworks hinder coherent climate adaptation responses. This is especially evident in the weak alignment between national strategies and municipal implementation, where local policies often lack enforceability or integration with disaster risk management plans (Matikinca et al., 2024).

Barriers such as climate change uncertainties and social/community challenges were ranked lower, possibly due to a technocratic bias among stakeholders prioritising infrastructure over softer, less tangible dimensions. However, high *CoV* for social issues signals divergent views, pointing to a lack of consensus on the importance of community engagement. This reflects a broader tendency to undervalue social vulnerability in infrastructure planning (Thorn, 2010).

In response, the study identified key strategies. Upgrading and maintaining infrastructure emerged as the top priority, indicating broad agreement on the urgency of modernising systems to withstand current and future climate threats. Schulze (2011) highlights the need for climate-resilient design standards, including flood-resistant infrastructure and drought-adaptive water supply systems.

Enhanced financial mechanisms, including PPPs, green bonds, and international climate financing, are critical to overcoming funding gaps. Dithebe et al. (2019) support innovative financing models that diversify revenue streams and improve creditworthiness, especially for financially struggling municipalities.

Strengthening governance and accountability is recognised as essential for enabling integrated and transparent decision-making. Mutanga et al. (2024) advocate for the WEF-H nexus framework to align multisectoral policies and foster resilient systems.

Moderately ranked strategies such as adopting climate-resilient technologies, investing in project management capacity, and promoting resilience to extreme weather highlight the long-term nature of adaptation. Vushe (2021) points to adaptive management approaches, like floodwater harvesting and decentralised systems, as cost-effective, scalable solutions.

Although policy and regulatory reforms and community engagement ranked lower, literature suggests they are critical for sustained progress. Legal frameworks provide the enabling environment for other strategies, while community involvement ensures relevance, ownership, and local adaptation capacity (Odeku & Meyer, 2010; Thorn, 2010). The undervaluation of these areas in practice suggests a gap between technical planning and socio-environmental needs.

Overall, the study revealed that while infrastructure and financial reforms are widely prioritised, deeper integration of social, governance, and environmental dimensions is essential for achieving sustainable and climate-resilient water infrastructure systems. The findings reinforce the need for a multi-dimensional, integrated approach to overcome entrenched barriers and develop sustainable and resilient water infrastructure to ensure water security in the face of climate change.

5. Conclusions

This study highlights the critical barriers and strategies for achieving sustainable and resilient water infrastructure in South Africa. The findings reveal that ageing infrastructure, financial constraints, inefficiencies in project management, and water resource scarcity are the most pressing challenges. Governance and policy barriers, along with social and community engagement, are perceived as less immediate but still relevant concerns. These insights align with existing literature, which emphasises the need for integrated water management, improved institutional coordination, and enhanced financial mechanisms to address these challenges effectively.

The implications of these findings are particularly significant for South African policymakers, municipal authorities, and water service providers operating within a context of growing climate risks, infrastructure backlogs, and socio-economic inequalities. Addressing ageing infrastructure and chronic maintenance deficits should be a national priority, especially in historically under-served areas such as rural provinces and peri-urban informal settlements. To overcome persistent financial constraints, municipalities must explore innovative funding mechanisms, including PPPs, municipal green bonds, and access to international climate finance through instruments like the Green Climate Fund. Strengthening governance structures—particularly at the municipal level—requires clearer institutional mandates, enhanced regulatory oversight, and reduced political interference in budgeting and procurement processes. Building technical and managerial capacity within local government is also essential to improve project planning, implementation, and monitoring. Additionally, integrating climate-resilient technologies, such as smart water metering, leak detection systems, and decentralised water reuse, can improve efficiency and adaptability. Importantly, although community engagement is currently undervalued in infrastructure planning, promoting public participation and local ownership is critical in South Africa's diverse and unequal society. Strengthening citizen awareness and involving communities, particularly in vulnerable regions, can improve accountability, foster behavioural change, and lead to sustainable and resilient water infrastructure and more equitable and sustainable water management strategies.

This study contributes to the growing body of research on water infrastructure sustainability and resilience by providing an empirical assessment of stakeholder perceptions. It underscores the importance of a multi-faceted approach that integrates technical, financial, and social dimensions to enhance water security in the face of climate change. By aligning these strategies with global best practices, South Africa can improve its adaptive capacity and resilience in water infrastructure development and management.

However, the study has certain limitations. The reliance on stakeholder perceptions may introduce biases that do not fully capture the complexity of water infrastructure challenges. Additionally, the study does not account for regional variations in water infrastructure needs, which may require tailored solutions. Furthermore, social issues such as corruption, including fraud, bribery, and misappropriation of funds, were not addressed, as they require dedicated investigation. Future research should incorporate quantitative performance evaluations, explore region-specific adaptation strategies, and examine social challenges to provide a more comprehensive understanding of sustainable and resilient water infrastructure development and management.

Conflict of Interests

The author declares no conflict of interests.

Data Availability

The data is available from the corresponding author upon reasonable request.

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