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ORIGINAL ARTICLE

Water management optimization challenges: a supply-side perspective

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Abstract

Potable water supply interruption is a reality in KwaZulu-Natal and is fast becoming the case for the rest of South Africa. From a supply-side perspective, water management faces significant barriers that hinder the effective and sustainable distribution of water resources. These challenges encompass ageing infrastructure, inefficiencies in resource allocation, and complex operating environments, all of which deflate the capacity to meet rising water demands. Disturbingly, such water supply interruptions, sometimes, leave water consumers without any substitute, which makes the situation more critical and collaterally emphasises the need for water supply to be managed optimally. It is in this backdrop that this study explores the optimization challenges water authorities and suppliers encounter by analyzing the technical, social, economic, and policy-driven barriers that encumber effective water resource management. Furthermore, it highlights red flags on water management and the effects of the decreasing water resources that have encouraged the continued implementation of water shedding, to the detriment of the population. The situation appears to be exacerbated by a growing population, climate change and dwindling water resources. In exploring supply-side limitations affecting the sustainable delivery of water, this study found limited resources, water loss, increasing costs, deteriorating and insufficiently maintained infrastructure, and complex administrations as hinderances to optimal water management.

Keywords Potable water · Water management · Optimization · Infrastructure · Supply chain

Introduction

The quest to optimize water management systems, represents a critical concern especially against the backdrop of increasing global challenges of water scarcity stemming from growing demand and climate variability, amongst others. The situation is not different among African countries. Driven by a concern about meteorological droughts particularly in Mauritius, Doorga et al. (2025) note that decline in rainfall, reducing surface and aquifer recharge and increased water consumption have led to severe water shortages in the country. In a study conducted in the context of Algeria by Hamlat et al. (2024), the researchers observed that the achievement of water-related sustainable development goals has been significantly impeded by natural water scarcity primarily caused by a cocktail of environmental challenges. Focussing on Nigeria, Gyau Baffour Awuah and Bijimi (2024) observe that the country faces a myriad of urban water supply challenges. In Zimbabwe, the persistent issue of poor water supply has been exacerbated by urbanisation, political instability and inadequate finance to fund critical water infrastructure developments (Maruta et al. 2023). Indeed, across the sub-Saharan region, Anghileri et al. (2024) aver that certain stressors such as changing availability patterns, growing population, and changing societal habits have created an unpalatable situation where most of the population does not have access to basic water supply.

Even though the situation is not different for South Africa, as issues related to access to water have become topical, findings from these studies may not apply to the specific

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South African situation given the geopolitical nuances of each country that dictate water management challenges. This notwithstanding, scholarly interest in investigating water management with country specific context is unsurprising, given the central place that water occupies in the equation of the quality of life for people. Indeed, one of the compelling reasons for the concern around water optimization challenges is that in South Africa, the Constitution expressly grants every person the right of access to quality drinking water (De Jongh et al. 2019). Owing to this Constitutional obligation, all spheres of government have a fiduciary duty to provide and ensure access to quality drinking water (Askham and van der Poll 2017) for the population. Unfortunately, the government appears to be struggling to fully deliver on the obligation of providing quality potable water to its citizens (De Jongh et al. 2019) as uneven and inadequate water distribution across the country (Maphumulo and Bhengu 2019) continues to be the sad reality. This is despite the position of the National Department for Water and Sanitation that recognises 'water as life, and sanitation as dignity'. It is this heightened premium accorded to water-related issues and the threat that inadequate access to water poses that has encouraged this study. In the main, the study seeks to examine water management optimization challenges in the context of one of two of South Africa's most populated provinces—KwaZulu-Natal (KZN).

Indubitably, water management optimization is critical in ensuring the sustainability of water resources, particularly in regions like KZN, which are facing increased water stress. The stress may be attributable to several factors, including population growth, urbanization, and climate change, which characterise the province (Nagan et al. 2023). Perhaps, this reality, amongst others, introduces several challenges to the effort of optimizing upstream water management systems, thereby complicating the ability of responsible authorities to maintain the correct balance between water demand and supply.

Markedly, the inability to satisfy the demand for water bodes dire consequences for the people of KZN and, indeed, the province itself, as the inaccessibility to sufficient good quality water has grave health and other implications for people. For instance, the situation leads to poor levels of sanitation that fertilise the proliferation of different water-borne diseases in the province. Such disease outbreaks can enormously strain the social fabric of the province, overburden hospitals, cause undue learner-absenteeism in schools and tease the people into massive protests that would adversely affect the socio-economic environment in KZN. From an economic perspective, the prevalence of poor health, owing to water and sanitation-related issues, would cause a decline in productivity levels across sectors. Certainly, this cannot augur well for a province that houses over 20% of South Africa's population (Statssa 2022). It is, therefore, a significant problem whose magnitude makes it deserving of scholarly attention if the undesirable situation of inadequacy of water for the people of KZN is to be ameliorated.

Disturbingly, there is a paucity of autochthonous studies on water management challenges in provinces with independent political systems and decentralized economic hubs, as well as how administrative, technical, and political decisions impact sustainable water provision (Golin et al. 2015; Olley et al. 2024). While important, extant literature addressing water management challenges tends to lack valuable geographical context (Omarova et al. 2019). This notwithstanding, on a global scale, water supply activists and scholars continue to caution about the water challenges from the perspective of several disciplines, including engineering, governance and environmental studies, but hardly from supply chain management viewpoint (Crookes et al. 2018; Kovela et al. 2018; van Huyssteen et al. 2023). Even the few studies that attempt to explore upstream-related challenges tend to follow a reactive firefighting approach as they address water-related challenges at the consumption level or demand end (Fathollahi-Fard et al. 2020). These shortcomings in extant literature justify the current study and more so in the context of KZN, a province in a country with a developing economy that rarely catches the attention of researchers concerned about water management issues.

To address this gap in literature, this study explores the water management optimization challenges encountered by water authorities and suppliers in municipalities in South Africa's KZN province from a supply-side perspective which is testament to its novelty. Specifically, the study focuses on technical, social and economic barriers that are encumbering water management optimization efforts in the province. Water demand constantly increases, yet the supply sources' yield is depleting (Crookes et al. 2018). The situation of escalating water scarcity amplifies the need to continuously study water management issues to duly inform real-time solutions. In essence, it is imperative to illuminate the challenges that obstruct the effort of water management optimization, as water is a human right and a critical resource of life. This would invariably have literary and practical value, but more than anything else, it would contribute towards a better quality of life for the people in KZN, which underlines the significance of the current study.

Water management in the context of KZN

A third of South Africa's population lives in areas heavily affected by drought (Al-Gamal 2020), climate change (Salehi 2022), a growing population, migration, and dwindling water resources that threaten sustainable water supply

(Kovela et al. 2018; De Jongh et al. 2019; Aina et al. 2023; van Huyssteen et al. 2023). Obviously, water scarcity is not unique to South Africa as 70% of the population in East Africa also lives in rural areas where water resources are under severe pressure, possibly because the region has experienced drought at least once a decade in the past 30 years (Al-Gamal 2020). More specifically, though the World Bank (2021) contends that per capita water availability is 728 m^3 per-person-per-year, in South Africa, as at 2024, this indicator is between 800 and 900 m^3 per-person-per-year (Moghayedi 2024) When these measurements are juxtaposed against the ideal water availability level that should be above 1700 m^3 per-person-per-year, based on the classifications of the World Bank (2021), South Africa can be described as a water-scarce country because its per capita water availability is below 1000 m^3 per-person-per-year.

For KZN, where more than two-thirds of the province comprises rural areas that are heavily dependent on agriculture and, therefore, water resources, the water inadequacy situation which is enabled by water management optimization challenges is likely to be very problematic. Incidentally, this situation is not limited to KZN, as a kaleidoscope of factors can exacerbate issues relating to water supply (Zulfiqar et al. 2021). However, the specific mix of reasons why the water inadequacy situation exists, given the geopolitical idiosyncrasies of the province may be unique. The implication of this is that findings of studies conducted in the context of different countries cannot be relied upon to infer what the exact situation would be in KZN.

This is particularly instructive because though the situation of challenges to growing water demand is not necessarily new, it has failed to receive the level of attention it deserves (Stambouli et al. 2014) perhaps because each situation is unique. This may be why although the government has implemented some water intervention programmes in KZN, emerging trends continue to point to persistent water supply challenges (De Jongh et al. 2019). The situation seems to persist because predominantly, demand-side approaches (Yates et al. 2005) have informed such interventions. The implication of this, unfortunately, is that the ever-growing water supply challenges remain. Markedly, substantial evidence on the issue of water scarcity links it to the absence of astute supply management (Al-Gamal 2020). If this is the case, then a laser-focused water supply management approach is required to address the growing concern about water scarcity. This is because, according to Aina et al. (2023), supply-side approaches in water management typically focus on designing and developing new water infrastructure, the maintenance of existing infrastructure as well as overall supply in a bid to ensure that the demand for water is met in a sustainable manner.

In this context, the current state of the evolving economy and the general environment present public organizations, with unique challenges hindering public service delivery (Din et al. 2025). These challenges may be best addressed by a drive towards multisector collaboration for effective public service delivery in response to the new challenges (Ansell et al. 2021). However, the focus on water sustainability so far has been on the last mile, which belittles the important role played by supply chain management at the upstream, regulators and policymakers, who invariably determine how water is sourced, managed and effectively distributed (Sahebjamnia and Fathollahi-Fard 2018). Despite this assertion, extant literature remains skewed towards ventilating demand-side management approaches to resolving water issues (Fielding et al. 2013) relative to the supply side. The lack of a water supply-side focus leaves, albeit consequentially, most supply chain issues relating to water provision unattended.

Proper supply chain management entails planning before the production line commences as this allows planners to assess the available capacity against the required output, thereby estimating realistic levels of fulfilment and turnaround times (Chopra and Meindl 2019). Furthermore, the importance of adopting a supply-chain focus is reinforced by the fact that supply planners periodically review forecasts based on historical data on demand and the future expected demand (Christopher 2022). Furthermore, the success and failure of a supply chain is often attributed to the extent to which there is collaboration, visibility and resilience.

Against this background, the supply chain in water provision may require a comprehensive periodic review of demand against the available supply in the form of infrastructure and planned developments against water resources. One benefit of the supply chain perspective is the appropriateness of decisions made because they leverage a futuristic view through forecasting, where descriptive variables are factored in to make estimates as accurate as possible (Mangan and Lalwani 2020). Demand-side approaches do not employ similar mechanisms and, therefore, tend to lead to the adoption of reactive strategies (Monczka et al. 2020). Certainly, such reactive strategies would not suffice as modern supply chains operate in a dynamic environment (Martins 2016), and this is not different in the water management domain.

Cognisant of this, South Africa's National Water Resource Strategy 3 of 2023 outlines ongoing water-related challenges and highlights the need for improved proactive upstream management. This position is motivated by a conviction that such an approach has the potential to effectively address a range of issues, including inaccessibility to water owing to water scarcity. So, the need for a systematic, long-term plan to address water-related challenges is imperative

(Couvelis and van Zyl 2012) regardless of their nature or source. Some challenges such as unregistered water meters and unauthorized consumption are major contributors to water losses in addition to traditional water leaks (Murugan and Chandran 2019). Other challenges include incorrect meter readings, data errors, and water actually delivered to consumers that are, yet recorded as losses to the municipality (Couvelis and van Zyl 2012). Regardless of the origins or the exact nature of the water-related challenges faced in the province, it is plausible that the reliance on a supply-side perspective may engender the crystallization of more sustainable solutions.

Study site and background

KwaZulu-Natal is the second most populated of the eleven provinces in South Africa. Being home to over 12,312,712 people (Statssa 2024), the province consists of one metropolitan municipality, ten district municipalities and 43 local municipalities. Located in a surface area that measures 94,361 square kilometres, the population density in the province is estimated at 131.7 people per square kilometre. Figure 1 shows the location of the KZN province in South Africa along with the municipal demarcation of the province. The province comprises 2.8 million households and has an average household size of 4.4. From an economy perspective, the provincial unemployment rate is estimated at 30.6% and the province contributes 16.2% to the national GDP (Statssa 2024).

The province is considered home to urban and rural dwellers. While noting the lack of universally accepted definition of rural and urban terms, this study adopted the definitions as provided by Mubangizi (2023) that are based on the Municipal Structures Act 117 of 1998 and the Department of Cooperative Governance and Traditional Affairs when describing urban and rural areas. Mubangizi (2023) notes that urban areas are characterized by high density, multiple businesses and industries, significant movements and economic activities as well as extensive developments. Conversely, rural areas are typified by scattered settlements built on communal lands. Communal lands often differ significantly from commercial farms as they have low population density, land tenure, and social conditions (Mubangizi 2023).

Industrial suburbs as well as formal and informal townships characterise the urban side of the province, while the rural side of the area is predominated by farms and homesteads. The urban side of the province inherited water infrastructure that the government installed during the country's years of apartheid and so residents in the urban side generally have direct water connections to their homes (Maphumulo and Bhengu 2019). On the other side, majority of the rural dwellers, who are predominantly black, have little or no direct water connections to their homes as the apartheid government's developmental agenda was deliberately skewed in favour of the urban areas inhabited by whites. So, communal standpipes and the river were the primary sources of water for most people in rural areas. Instructively, the greater part of the KZN province is categorized as rural (Hofstetter et al. 2020).

Methodology

The interpretive paradigm was better aligned with this study, as interpretivism is often associated with qualitative research (Rahman 2017; Saunders et al. 2020) and so it was adopted. Considering the dynamic nature of water management challenges, this approach is better suited to collating rich information (Clement et al. 2018). This inductive study, therefore, entailed soliciting the views of managers within the water and sanitation department responsible for water supply in identified municipalities in KZN. The adopted

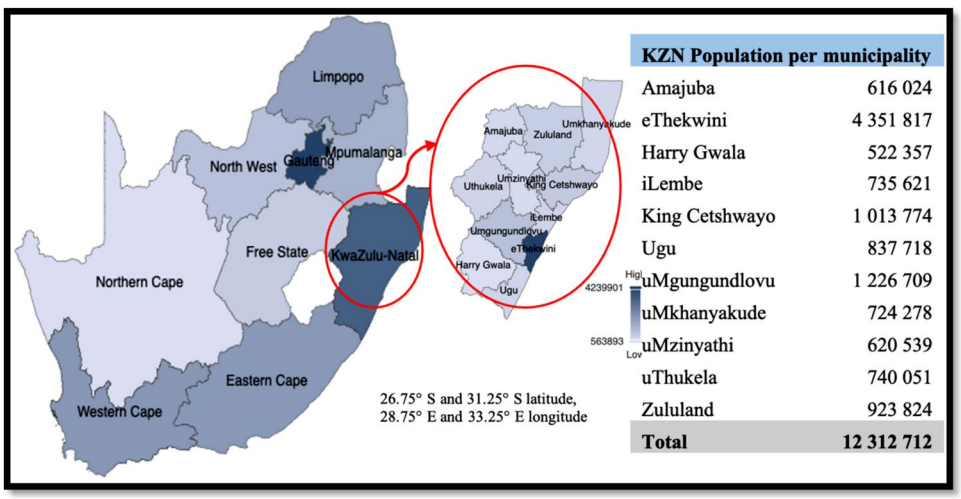

Fig. 1 Location of KwaZulu-Natal (KZN) in South Africa and population distribution in the province

approach was beneficial as it allowed for informants to be interviewed in natural settings—their places of work. According to Cardano (2020), such a setting facilitates cross-referencing and triangulation with supporting official documents that are readily accessible to them. Triangulation was realized by relying on existing literature, publicly available policy documents and institutional official reports. In their seminal work, Lincoln and Guba (1985) describe transferability as the extent to which the findings of a study can be transferred and be applicable in other settings.

Using a qualitative case study was apposite for this study because, as observed by Crowe et al. (2011), it can foster understanding of issues of interest in their natural, real-life context. Against this backdrop, this study adopted the case study approach as an appropriate strategy since the water management challenges in KZN are multidimensional and complex in nature. The study benefitted as it investigated deeper challenges facing the municipalities. Metropolitan and District municipalities were sources of information-rich key informants and at the forefront of provincial water regulation and distribution. Potable water distribution is the responsibility of the district and metropolitan municipalities within the province. Instructively, similar to what Omarova et al. (2019) observed in Central Kazakhstan, KZN, being predominantly rural, suffers from urban-driven decisions designed to address across-the-board challenges (rural and urban).

In order to undertake the study, permission was sought and received from the National Department of Water and Sanitation as well as the respective municipalities in KZN. The municipal Manager's Office was approached in each Municipality and the background, core purpose and research questions of the study were elaborately discussed. Though eleven municipalities were contacted, only seven elected to participate. As it pertains to participants specifically, the study targeted at least one employee from each of the three management levels (strategic, tactical and operational) in each municipality. Organization structure-wise, directors are at the strategic level, deputy directors are at the tactical level and senior managers are at the operational level. Occupants of these positions in the water and sanitation department were targeted by the study because they saddle the responsibility for water provision in KZN's metropolitan and district municipalities. Accordingly, the office of the municipal manager in selected municipalities were contacted to assist in identifying the relevant directors or managers and enable the researchers access them for interviews. Effectively therefore, the study relied on a purposive sample of participants as it enabled the application of the key-informant technique. With this approach, the study was assured that only those who were sufficiently knowledgeable about water management optimization challenges in each municipality would partake in the study.

The interviews were semi-structured in nature and so a discussion guide was developed and pre-tested among selected supply chain experts before it was used to collect data. Preliminary questions to gauge current knowledge and previous experiences were included in the discussion guide to establish the participants' suitability. These were necessary to ensure that the opinions shared by the participants were well-informed and reflective of rich and in-depth understanding of the water management landscape. In total, thirty eligible participants were contacted across the seven municipalities but only nineteen who were willing and available to participate, were eventually interviewed. However, only eighteen (18) interviews were deemed suitable for analysis as one of the interviews provided content that was deemed irrelevant to the study, even though the participant met the inclusion criteria. Table 1 provides a synopsis of the profile of the participants who were interviewed.

Open-ended questions in the discussion guide were posed to the participants, and the discussions were audio-recorded and transcribed individually by the researchers, within two days of each interview. The semi-structured interviews allowed the researchers the liberty to explore a wide range of issues related to water management optimization challenges. Following data collection, the primary data from interviews were organized and examined using thematic analysis because, according to Nowell et al. (2017), the technique can be used to identify, analyse, organise, manage, describe, and report on the themes identified in the dataset.

This study was conducted in accordance with the criterion for trustworthiness in research as set by Lincoln and Guba (1985), namely, credibility, dependability, transferability and confirmability, thereby demonstrating scientific rigour. Credibility refers to the research instrument's ability to accurately collect and maintain informants' views and perceptions to be reflected in the findings (Stahl and King 2020). For credibility, this study ensured that a conducive and comfortable atmosphere existed for the semi-structured interviews and that these were personally conducted by the researchers. Stahl and King (2020) describe dependability as the extent to which consistency and stability are maintained in a study. Dependability assesses the extent to which results consistent with the initial study could be obtained if a similar study were to be carried out under the same conditions. Dependability was ensured by adherence to the suggestion of Creswell and Guetterman (2020) that a clear audit trail with a detailed description of the methodology and implementation be maintained.

Following the suggestion of Polit and Beck (2020), the researchers have carefully stored detailed information about

Table 1 Participants' profile

Participant pseudonym	Job title	Management level	Organization pseudonym	Experience
P1	Senior project manager	Operational	A	10 Years
P2	Deputy head in water and sanitation	Tactical	B	4 Years
P3	Project executive: water and sanitation (deputy director)	Tactical	B	14 Years
P4	Senior executive: commercial and business (deputy director)	Tactical	B	22 Years
P5	Senior manager: planning for water and sanitation	Operational	B	32 Years
P6	Institutional social development officer (manager)	Operational	C	9 Years
P7	Deputy director: operations and maintenance	Tactical	C	3 Year
P8	Customer care deputy director	Tactical	C	8 Years
P9	Senior executive: planning and integrated development planning	Tactical	D	9 Years
P10	Senior manager: water services	Operational	D	4 Years
P11	Senior executive manager: water services (deputy director)	Tactical	D	6 Years
P12	Operations manager	Operational	E	5 Years
P13	Director: municipal infrastructure implementation	Strategic	E	3 Years
P14	Head of department: water and waste process	Strategic	E	5 Years
P15	Water engineer (manager)	Operational	F	3 Years
P16	Head of department: operations maintenance	Strategic	G	4 Years
P17	Credit control officer (manager)	Operational	G	2 Years
P18	Deputy director: customer care section	Tactical	G	2 Years

the participants, the sites where they were interviewed, the sampling strategy, and the reasoning behind the methodology utilized as this would ensure correct judgement is made for transferability purposes. Confirmability is another criterion for trustworthiness, as outlined by Lincoln and Guba (1985), it focuses on the degree to which findings are shaped by the experiences, views and perspectives of those interviewed rather than researcher biases, motives and assumptions. To this end, the Atlas.ti software for qualitative analysis was used for data capturing and an audit trail was maintained while carrying out the research.

Results and discussion

In this study, the issue of water management optimization challenges was demarcated into five sub-themes: resources, water loss, costs, infrastructure, and administration. Table 2 provides an overview of these sub-themes along with the axial codes that informed them. Sub-themes and participants who responded to them demonstrated how unstructured data provided during the interview stage were used to systematically categorise interview excepts to find patterns as part of the data analysis.

Information presented in Table 2 shows that the sub-theme to which most responses were provided was that of administration. This is then succeeded by the sub-themes of infrastructure, costs, resources and water loss. The predominance of administration-related responses is unsurprising as many of the study's participants occupy high-level administrative positions. Additionally, the distribution of responses, as depicted in Table 2, signals that the concern of participants with respect to water management optimization challenges pivots mostly around administration, infrastructure and cost-related issues.

Resources

According to some participants, the issue of limited resources was a common factor in the seven municipalities. Interestingly, the issue of limited resources was also identified as a factor hindering water-related infrastructure development in Zimbabwe (Maruta et al. 2023) which according to Hoko et al. (2024) is partly due to poor revenue collection. Similar to the situation in Zimbabwe, the extent to which revenue collection and management happen, differentiated one municipality's financial status from the other. Mirroring the findings in Nigeria by Gyau Baffour

Table 2 Sub-themes and source of responses

Sub-themes	Participants (P)																		Total number of responses
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
1. Resources																			**22**
Finances	x	x	x			x	x		x	x	x	x						x	
Skills	x	x							x	x	x			x					
Non-payment culture	x		x			x				x	x						x		
2. Water loss																			**19**
Water leaks	x	x	x	x	x	x			x	x	x			x			x		
Illegal connections	x	x	x	x	x	x				x	x								
3. Costs																			**32**
Alternative supply/providing water	x	x	x	x	x	x	x		x	x	x	x	x	x		x		x	
Area coverage	X	x	x	x	x		x	x	x		x	x	x		X	x		x	
Topography						x	x				x								
4. Infrastructure																			**34**
Ageing	x	x				x		x	x	x	x	x		x					
Backlog																			
Design	x	x	x			x			x	x	x			x	x		x		
Load shedding	x	x	x								x					x			
Water shedding		x		x	x	x	x		x	x	x	x		x			x	x	
5. Administration																			**42**
Planning		x	x			x	x		x	x	x		x	x		x		x	
Migration		x	x								x	x		x		x		x	
Capacity constraints	x	x	x	x		x			x		x	x	x	x	x	x		x	
Political intervention	x		x	x		x				x	x	x		x	x		x	x	

Awuah and Bijimi (2024), several participants argued that financial status primarily dictates the municipality's ability to deliver on its mandate without relying heavily on grants. This notwithstanding, the 'resources' sub-theme comprises three codes: finances, skills and non-payment culture. From a financial perspective, participants opined that allocated budgets are quite low and cannot sustain equitable water provision. It was also suggested that some of the municipalities' revenues are channelled towards subsidizing residents that are classified as indigent, which further depletes the already limited financial resources. With regards to skills, participants noted the challenge of attracting skills that are willing to be deployed to rural areas being serviced by the municipalities.

It was deduced from the participants' opinions that due to the high level of unemployment in rural communities, residents attempt to force the municipalities to hire locals, regardless of the level of skills required. This leaves most municipalities with unfilled vacancies, which has implications for effective water management. The prevalent high level of unemployment, in concert with other socio-economic factors, also feeds the culture of non-payment by water users. Participants identified the culture of non-payment for basic services as an important factor impacting resource availability for effective water optimization management. In the words of some participants relating to the three resource-related codes:

> P1: "We did a study some years ago to try and determine how we would need to provide water throughout the entire area. We found that we would need about R800–R900 million. At that time, about four years ago, it was equivalent to spending about R150 000 per household, though the threshold set for Water Affairs is R40 000 to R50 000 per household. So, it is not sustainable."

> P10: "We want employees (HR) that can do the actual job... but we do not have the financial muscle to hire the requisite skills or required resources….or, sometimes, you find that they are not readily available in the market."

> P9: "The consumers who are the recipients of the water that we are producing are supposed to pay for it, but they are not."

> P17: "To win support, during electioneering campaigns, some politicians tell people that they do not need to pay for water. If your local councillor were to tell you not to pay for water, would you pay? This is the most challenging thing we are facing."

Water loss

Water loss represents a direct and indirect cost to the municipalities. The water loss sub-theme comprises two codes: illegal connections (non-revenue water) and water leaks. Most participants indicated that available water sources were scarce; therefore, any measures that could preserve water are invaluable. As expressed by some participants, the integrated development plans of the municipalities have limitations, as they merely cater for forecasted demands and make no provisions for possible water losses arising from illegal connections or leaks in the pipe network.

Municipalities are aware that they are experiencing water losses; however, technical managers are unsure where such leaks and losses emanate from. Admittedly, it is quite difficult to reduce such water losses as municipalities are unable to determine the exact points of leakages and illegal connections in the system. In the words of some participants,

> P1: "Some areas are now recording up to 70% water losses. If you can reduce water losses, you might need very little from the source. One way to do that is to assess the entire water supply chain and value chain to check how we can improve or make our water supply more efficient."

> P14: "This relates to education, and people must take ownership of water losses. There is a perennial problem with leaks, which creates challenges for us. Strangely, people don't even report those leaks until the municipality picks them up."

> P10: "At the operational level, we have people connecting illegally to the system. The sad part is that you don't even know how many of them or who they are. So, you can't even go and say you're going to disconnect such."

> P11: "You find that there is a huge gap in terms of the water supplied, but in terms of the records, the people that are metered, you probably sold half of that."

Costs

Cost was another important sub-theme that emerged in this study and is made up of three codes: alternative supply (providing water), area coverage, and topography. Markedly, the issue of costs that exacerbates water management challenges was also noted as a major concern in Algeria (Hamlat et al. 2024) as well as in Zimbabwe (Hoko et al. 2024). In relation to alternative supply, municipalities are required by law to arrange alternative water supply in the event water

distribution is interrupted for six consecutive hours. With respect to this, several participants argued that the ward size and area classifications are noteworthy as they determine the number and frequency of water tankers to be deployed. Worrisomely, water distribution through tankers is a contingency plan in urban areas, while it is a standard water distribution channel in rural areas. Secondary data credited to the National Water Resource Strategy 3 of 2023 indicates that 3316 water tanks were deployed across the country in 2020/21, and this is a substantial number that reflects the frailties in the standard water distribution network. Most participants aver that the situation is no different in KZN, as eighty-five per cent of the municipalities in this study are located in rural areas. Area classification is essential in this study as it justifies the rationale behind the type of infrastructure roll-out in rural areas compared to urban areas. Spatial and topology issues also adversely affect water provision, forcing rural dwellers, in some cases, to personally invest in alternative water supply initiatives.

The rural part of KZN is a mountainous region, and the specific areas that are inhabited are sparsely populated. Consequently, the task of laying water infrastructure becomes quite complex, and the delivery of water sometimes requires booster pump stations as the pipes run over undulating terrains. According to some participants, the challenge posed by the wide dispersion of consumers does not exist in urban areas because strict town planning ensures that houses are next to one another, and this eases the connection of houses to the main water supply pipelines. In addition, some participants noted that different types of planning are undertaken by different departments, mostly in silos and resultantly some of the plans are misaligned with one another. For instance, plans for human settlements are sometimes created without proper coordination among relevant government departments which would have allowed for the capacity to deliver water to such areas to be carefully considered. This puts further strain on the existing but already debilitated water infrastructure.

Furthermore, another challenge found to hinder the optimization of water management is the layout and disaggregated distribution of multiple smaller water treatments in rural areas. This topography poses serious engineering and funding challenges that have implications for the supply of water, especially for rural communities. Evidence from participants in relation to alternative supply, area classification and topography signal that:

> P1: “Some of the challenges are the rudimentary water supply, such as the water tankers, which are quite costly. Some of the areas are high-lying areas, and you have no option but to provide water using water tankers. It’s not sustainable to have pipes going to one household here and another there when they are significant distances apart.”

> P6: "Our main water source is at the bottom of the mountains. But the communities we must supply water to with the system we built are at the top. Now, you can see how expensive it is to finance the infrastructure that we must put in place to pump the water up the mountain.”

> P10: “We’ve got areas where when we talk interruption, it may be a seven-day interruption where you have no water, and then next week you have water and then the week after you don’t...in such cases, you must deploy water tankers.”

> P15: “The Department of Human Settlements went on to build many low-cost houses without engaging with us. This fragmented planning approach is problematic. We just saw construction taking place, and we didn’t know anything about it. As the Technical Unit responsible for water management, we were never involved and could therefore not assist in assessing and advising on the capacity of the existing water infrastructure to supply the proposed 2000 houses.”

Infrastructure

There are five codes under the infrastructure sub-theme: ageing, backlog, design, load shedding and water shedding. According to some participants, all the urban parts of the districts are characterized by ageing infrastructure, while the rural parts have very sub-standard infrastructure and very little water running through it. A similar issue related to poor state of infrastructure was also found to inhibit effective water management in Ethiopia (Meskele et al. 2023), and Nigeria (Gyau Baffoour Awuah and Bijimi 2024). Though over the years, in South Africa, different districts have managed to eradicate the backlog in water infrastructure provision in some rural areas, the level of the water infrastructure in such areas leaves a lot to be desired as they are at best, of low rural standards.

Regardless of the area—urban or rural—this study found that from a capacity perspective, existing infrastructure cannot cater for the population growth, and this finding aligns with results of the study by Anghileri et al (2024) on nine transboundary river basins in Sub-Saharan Africa. Statssa (2022) estimates that the population in South Africa grew by 19.8% from 2011 (51.7 million) to 2022 (62.0 million). The water provision and population mismatch are because in the same period, the capacity for water supply to dwellings only grew by 13.4%. The situation in KZN is not dissimilar as the

population grew by 17.4%, but access to water only grew by 11.8%. In both cases, nationally and provincially, it is obvious that the population is growing faster than dwellings are being supplied with potable water. Beside the capacity of the existing infrastructure, the water schemes in rural areas are not designed in an integrated manner that supports and feeds into one another. Instead, rural areas have multiple smaller water schemes supplying smaller areas; as such, this requires extensive resources to maintain and to manage.

In relation to infrastructure design, the challenge seems to relate to balancing sustainability, equity, and functionality. In urban areas, the existing design fails to address ageing and overburdened systems and barely incorporates contemporary solutions to manage rapid urbanization and increasing demand. The outdated layouts often limit retrofitting for efficiency or water reuse. In rural areas, infrastructure design faces logistical hurdles like difficult terrain, widely dispersed populations, and limited funding, which partially aligns with what was observed in Sab-Saharan Africa by Anghileri et al. (2024). The existing water infrastructure designs in rural areas appear to be inconsiderate of critical issues like climate resilience or efficient maintenance. Across rural and urban areas, fragmented planning, inadequate stakeholder coordination, and failure to adopt integrated, adaptable designs further complicate water optimization aspirations.

While water-shedding plans may be regarded as a contingency measure to prevent taps from drying up, their persistent nature has become problematic. It is, therefore, unsurprising that across the province, the temporary solution of water-shedding was identified as a challenge. Interestingly, while water shedding is typically implemented in the short term in urban areas, it seems to have been adopted as a long-term intervention for rural areas. Scheduled water shedding, which is tantamount to the rationing of supplied water, is controlled by the municipality and applied in a bid to preserve available water. This practice may become even more frequent in the future, given the reality of aged infrastructure and dwindling water resources across the province. In relation to the infrastructure sub-theme, participants opined that:

> P11: "Most of the water infrastructure were built some 7– 20 years ago, and many have reached the end of their useful lifetime, as situation that has been quickened by a poor maintenance regime. The government should have known this and therefore made plans to replace it or done something to refurbish it. So, the government has not done that and so it is becoming porous; we are therefore forever going behind it and trying to plug holes."

> P15: "The infrastructure is bad, as most have been there for years. They are characterized by constantly bursting and retrofitting; you cut and join. But half a kilometre from wherever you made a pipe joint, if there is a new pipe burst, then where you had joined becomes the weakest link."

> P18: "The backlog is around 19-20%. In that 20%, some areas were reticulated, and there were pipes put into the respective homesteads, especially in the rural areas. Due to the dwindling rainfall that is partially relied upon as a source, water is no longer there. When you open the tap there is no water coming, and so you need to supply water to the people through water tankers."

> P17: "There are operations in remote areas in that we have a plant at the bottom of the hills, and this makes it expensive to operate. In total, the district has 53 processing plants and with the current design, our planning got lost somewhere, as this is not sustainable. The big cities like the City of Cape Town and Johannesburg have on average of 23 water treatment and six big wastewater treatment plants".

> P13: "The system we are currently using is based on an alternated supply. This means that on Mondays and Tuesdays, certain areas of the municipality will be supplied with water, and on Wednesdays and Thursdays, the water supply will be channelled to other areas. So that is how we survive; we have no other option."

Administration

The administration sub-theme encompasses four codes—planning, capacity constraints, migration and political intervention. Markedly, it is difficult to determine the capacity of existing infrastructure with confidence because limited data is available for planning. Furthermore, capacity-related constraints are also exacerbated by the uncoordinated planning that takes place across the province. Indeed, capacity constraints were explicitly credited with limiting water reticulation in six of the seven municipalities in this study. Consequently, available water treatment plants cannot satisfactorily service the existing demand, which has increased significantly due to migration to the rural areas of KZN. The erratic nature of the migration makes it extremely difficult to cater for, in planning for water supply. Additionally, the substantial time lapse between planning and implementation sometimes means that whatever has been implemented ends up being dated, such that water system provisions, unfortunately, fall short of current water demand levels.

In relation to political intervention, this study found that while political influence can either be positive or negative, its implications at the local government sphere can be profound. This is because decisions and resolutions, which are expected to be participatory and democratic, largely depend on issues trading between councillors. Consequently, the role of political intervention in water supply-related decisions is heightened as it has a cascading effect on other challenges facing water provisions. Indubitably, overreaching and misusing of power by local councillors to score political points hinders effective water supply. In the opinion of some of the study's participants:

> P10: "We need to really focus more on how we plan. These plans must be informed by our ability to predict and project growth and demand, or increasing demand for water and sanitation, as the two services that we mainly provide."

> P17: "People are no longer moving out of rural areas. You find people from urban towns moving back to rural areas. This has increased the overall water demand and more so, because the average water usage has also drastically risen from 25L per-person-per-day (pppd) to approximately 65L pppd."

> P11: "We implement disconnection when we see fit, but often we receive calls from furious political principals, saying that we only implemented disconnections in their wards as this puts them at a disadvantageous position, especially when they [political parties] are planning to embark on political campaigns."

> P3: "There needs to be synergies arising from cooperation between operations within the municipal administration and the political contingent, between the bureaucrats and the politicians, as this enhances the quality of decisions and resolutions made in relation to water-management issues."

Conclusion

From a supply-side perspective, water management optimization challenges arise from the inherent complexities in available resources, water loss, costs, distribution infrastructure, and administrative measures in place. Additionally, the governance structures and regulatory frameworks are not promptly responsive to emerging issues like the evolving political landscape, growing population, water leaks in the systems and water scarcity, among others. These challenges are further exacerbated by the need for cross-sector collaboration between municipalities, industries, and agricultural sectors, each with differing water demands and resource management capabilities.

Interestingly, under the resources theme, while all participants identified inadequate finances as a common challenge, some highlighted a dearth of skills and the culture of non-payment as perennial issues. The case of lack of requisite skills was especially pertinent, particularly in rural areas, as potential candidates were not willing to relocate to rural areas, and the municipalities are not financially buoyant enough to pay attractive salaries for people to relocate to rural areas. Compounding the situation of limited resources already faced by the studied municipalities, the study also found that their existing revenue generation model is ineffective such that even when water is supplied, there is a low level of revenue collection for it.

Regarding the water-loss sub-theme, the study's findings revealed leaks and illegal connections as the major water management optimization challenges. Interestingly, illegal connections were encouraged by longer lead times from the municipal side, as participants indicated that some communities lose patience waiting for municipalities to connect them to the network and end up connecting themselves. Municipalities are also faced with incurring additional costs of providing alternative water distribution points due to disruptions in water supply. This is partly because system maintenance plans are not religiously implemented, leading to more frequent breakdowns. Electricity load-shedding is also a unique challenge because its occurrence results in power outages and a consequent shutdown of the water distribution network.

With respect to administration, this study found that there is a growing trend of people migrating to rural areas, yet water-related infrastructure development fails to take cognisance of this drift. Also, the dynamics of the political environment complicate water optimization efforts as municipal councils responsible for decision-making are formed by different political parties. Invariably, where political parties place their interests above service delivery considerations, water distribution decisions sometimes become skewed in favour of geographical areas that are aligned with certain political parties to the detriment of others.

The findings of the study have theoretical and practical implications as they contribute to an improved understanding of the contemporary autochthonous water management challenges in the KZN province. It is novel and contributes to enriching the body of knowledge as the issue of water supply optimization for a large province like KZN in a developing economy is yet to capture the interest of scholars. This is particularly important as there are limited studies investigating water management challenges under the circumstances of participatory government, where regulation

sits at the national government level, but management is delegated to district municipalities governed by a mix of political parties.

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Data availability Data supporting the findings of this study are available from the corresponding author upon reasonable request. The data has not been made publicly available due to conditions associated with ethical considerations and privacy.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical approval The authors affirm that this work complies with all ethical standards and that any necessary permissions for data and third-party content have been obtained.

Consent to participate Prior consent was sought from the municipalities and the informants that participated in this study.

Consent to publish The authors declare their consent to publish this work.

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