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Institutional Arrangements and Roles within Water and Wastewater Treatments in the Vhembe District, South Africa

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Abstract: Water scarcity is a global challenge faced by millions of people, and it has a negative impact on the ecosystem, public health, and financial stability. Water demand and supply management becomes critical, especially in areas with limited access to clean, safe water. Wastewater and water treatment infrastructure is essential for maintaining environmental integrity and protecting human health. However, water treatment plants in South Africa face various complex obstacles brought on by institutional setups, practical limitations, and environmental concerns, including water quality. This study investigated the institutional arrangements, operational challenges, and environmental concerns that water and wastewater treatment plants face in the Vhembe District Municipality, South Africa. A qualitative study was conducted in Limpopo province, where employees from 12 water and wastewater treatment plants were interviewed, and the data were analyzed thematically. The data were arranged into five major themes using thematic analysis: understanding water and wastewater treatment systems, educational and demographic profile, water quality assessment, operational performance and regulatory compliance, and water volume in waterworks plants. Staff attitudes, institutional and operational challenges, and the current condition of treatment plants were all comprehensively portrayed using Ostrom's IAD Framework. It was found that workers generally understand water treatment processes, but inconsistencies and a lack of transparency in monitoring water quality were noted, with many parameters from SANS 241 not being tested consistently. A significant educational gap among workers was also observed. Insufficient capacity, load-shedding, limited resources, and inadequate infrastructure prevented treatment plants from meeting daily water needs, worsened by institutional and socio-economic factors. Similar challenges were noted in countries like China, Ethiopia, India, Pakistan, Malaysia, Brazil, and Libya. To enhance water management efficiency and compliance, the study recommends more training, standardized procedures, proactive maintenance, and stakeholder involvement.

Keywords: wastewater; wastewater treatment works; human perceptions; water management; institutional factors

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1. Introduction

Water shortage is a major concern worldwide [1]. According to the World Health Organization [2], over 2.1 billion people cannot access clean drinking water globally. Africa is the second driest continent after Australia, possessing only 9% of the world's renewable water resources to support approximately 15% of the global population [3]. According to a report, 411 million people in Africa did not have access to basic services for drinking water in 2020 and 779 million people lack access to sanitation services [4]. Water shortage is a result of inadequate and malfunctioning water and wastewater treatment facilities in Africa, particularly given the continent's rapid urbanization and population growth [3,5,6]. Water and wastewater treatment plants are crucial for preserving environmental integrity and protecting public health by cleaning water to acceptable environmental and human health standards [7,8]. Water treatment plants ensure the availability of safe drinking water by removing harmful contaminants and pathogens, while wastewater treatment plants reduce pollutants before water is released back into the environment [8,9]. These treatment facilities contribute to reducing the danger of waterborne illnesses and promoting sustainable water supplies for communities [7–9].

More than 3 million people in South Africa still lack access to a basic water supply service, and 14.1 million people are without access to safe sanitation [10]. The Department of Water and Sanitation [11] reported that South Africa has limited water resources and projections indicate that by 2025, there will be more demand for water than supply due to growing demands from competing users such as agriculture and mining industries. The local and district municipalities in South Africa are responsible for treating wastewater in their respective areas. One example is the Vhembe District Municipality (VDM) in Limpopo, located in the northernmost province. Murei et al. [12] reported that majority of the water sources in the Vhembe District Municipality are unsafe for human consumption due to persistent fecal pollution, given that many people rely on surface water for drinking and other household purposes. The lack of water treatment infrastructure and poor sanitation practices in rural communities are linked to the spread of cholera epidemics [13,14]. The 2023 cholera outbreak in Hammanskraal, Gauteng Province, shows a serious problem of limited access to potable water, with the Rooiwal facility identified as the outbreak center [15].

According to the Constitution of South Africa [16], access to sufficient and safe water is a fundamental human right, essential for survival. Section 27(1)(b) states that "everyone has a right to have access to sufficient food and water". Since independence in 1994, the South African government has made significant efforts to address rural inequalities and poverty inherited from the apartheid era [17]; however, access to water services in most rural communities remains a big challenge. In recent years, the country's drinking water treatment infrastructure has expanded, with more than 1300 drinking water treatment works (WTWs) now in operation [18,19]. However, significant challenges remain, particularly in wastewater management. According to the Green Drop Watch Report 2023, there are 850 wastewater treatment works (WWTWs) across 144 municipalities, with 334 of these plants in a critical state [20]. Despite efforts to improve infrastructure, persistent water access issues remain a significant barrier, as reported by Edokpayi et al. [18] and Moropeng et al. [21]. These latter studies highlight the failures in achieving sustainable access to clean water in rural areas as a systemic problem, including low investment, inadequate maintenance of existing infrastructure, and a lack of focus on rural community needs. To ensure the sustainability and sufficient availability of water resources, Idoga et al. [22] and Obasa et al. [15] emphasize the need to strengthen institutional functions and adopt innovative approaches that encourage responsible management of water resources.

Institutional arrangements refer to the formal and informal norms and standards that define decision-making authority over shared resources, such as water, and the specific decisions related to its usage, management, enforcement, and monitoring [23]. Ostrom et al. [24] developed the Institutional Analysis and Development (IAD) framework, which identifies key variables that influences the function of institutions in shaping social interactions and decision-making processes [25,26]. According to the IAD framework, three primary variables must be considered: (i) "attributes of the community", (ii) "biophysical conditions", and (iii) "rules-in-use" (Figure 1) [26]. The "attributes of the community" refer to characteristics of each stakeholder group—such as citizens, government organizations, and industrial producers—that influence their decision-making processes [26]. The "biophysical conditions" encompass both constructed and natural environmental aspects of the issue at hand [26]. Lastly, the "rules-in-use" indicate the formal and informal rules and customs that govern the situation [26]. Ostrom's IAD framework has been effectively applied in various contexts, including assessing the effectiveness and sustainability of soil and water conservation initiatives, analyzing community participation in water use governance from alluvial aquifers, and understanding the political–economic dynamics contributing to air pollution while suggesting alternative solutions [25–29]. This study aims to assess the institutional arrangements, operational challenges, and environmental concerns affecting water and wastewater treatment plants in the Vhembe District Municipality. To achieve this, the study examines the governance structures affecting plant operations, assesses the operational challenges such as infrastructure and capacity constraints, and explores the environmental issues impacting plant sustainability such as water quality.

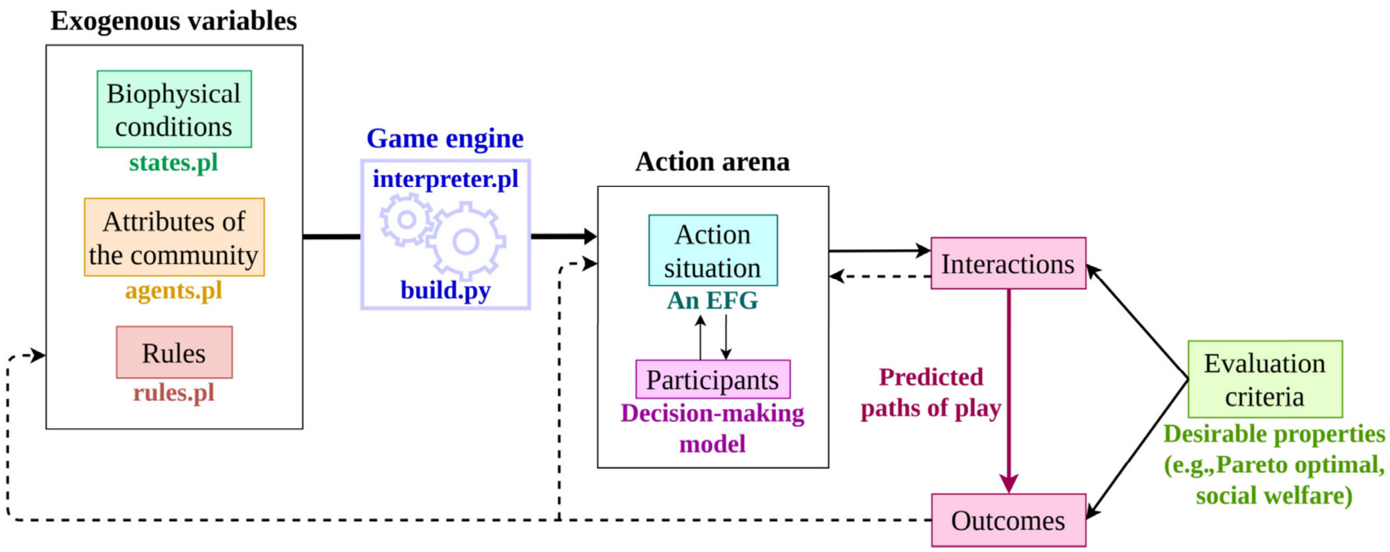

Figure 1. Institutional analysis and development framework with thematic analysis. Colored text outside boxes indicates either the scripts that contain information on the boxed component, and/or the game-theoretical concepts that represent it. Adapted from Montes et al. [30].

2. Methods

2.1. Research Ethics

Before conducting the study, application documents were submitted to the District Manager of Vhembe District Municipality, seeking permission to conduct a study on water and wastewater treatment works within the district. The study was conducted only with the consent of the participants; no one had to be forced by the researchers to take part. We ensured compliance with informed consent requirements and protected participant privacy by adhering to two common standards: (1) secrecy and (2) anonymity. Through in-person interviews, managers and process controllers from wastewater and water treatment plants provided qualitative data for the study. Every name was crossed out and replaced with an alphanumeric code in all the notes and transcripts. Access to the consent forms and hard copies of the interview notes was restricted to the researchers, who stored them in a locked box.

2.2. Study Area

The study was conducted in the Vhembe District Municipality (VDM) (category C, meaning a municipality that has municipal executive and legislative authority in an area that includes more than one municipality—https://www.justice.gov.za/legislation/constitution/SAConstitution-web-eng-07.pdf, accessed on 17 September 2024), consisting of four category B (a municipality that shares municipal executive and legislative authority in its area with a category C municipality within whose area it falls—https://www.justice.gov.za/legislation/constitution/SAConstitution-web-eng-07.pdf, accessed on 17 September 2024) local municipalities: Collins Chabane, Thulamela, Makhado, and Musina. Vhembe District Municipality is situated in the northern region of the Limpopo province, sharing borders to the east and west with the Capricorn and Mopani District

Municipality [31]. According to Statistics South Africa's 2022 community survey, VDM covers an area of 27,969,148 km^2, with a population of approximately 1,653,022. The district has 21 water treatment works, and 28 wastewater treatment works recorded, and 13 of them are not owned and operated by the Water Services Authority [31]. Two local municipalities were selected in this study, which were Thulamela and Makhado Local Municipalities. Table 1 shows the demographics of the two local municipalities.

Table 1. Demographics of two selected local municipalities within the Vhembe District Municipality, South Africa. Data source: Statistics SA [32].

Municipality	Population	Male (%)	Female (%)	Educational Institution Attendance (%)	Working Age (15–64 Years) (%)	Young (0–14 Years) (%)	Formal Homes (%)	Access to Piped Water (%)	Access to Flushed Toilets (%)
Thulamela Local Municipality	575,929	46.6	53.4	83.2	61.7	31.8	96.4	26.0	28.1
Makhado Local Municipality	502,397	47.0	53.0	81.9	61.6	31.3	94.7	26.0	29.7

Six sewage treatment works (STW) were sampled, which consisted of activated sludge (n = 4), oxidation package (n = 1), and package plants (n = 1) (Figure 2), with a capacity of 0.25–3.94 million liters per day (MLD). The plants experience sporadic incidents, with the Makhado STW being regular in terms of incidents. The water treatment works (WTWs) fell under the regional bulk WTW class (n = 4), with two belonging to the internal bulk WTW class. The capacity a day ranged from 2.85 to 18.9 MLD and the 3 and 3 WTWs experienced periodic and regular incidents, respectively.

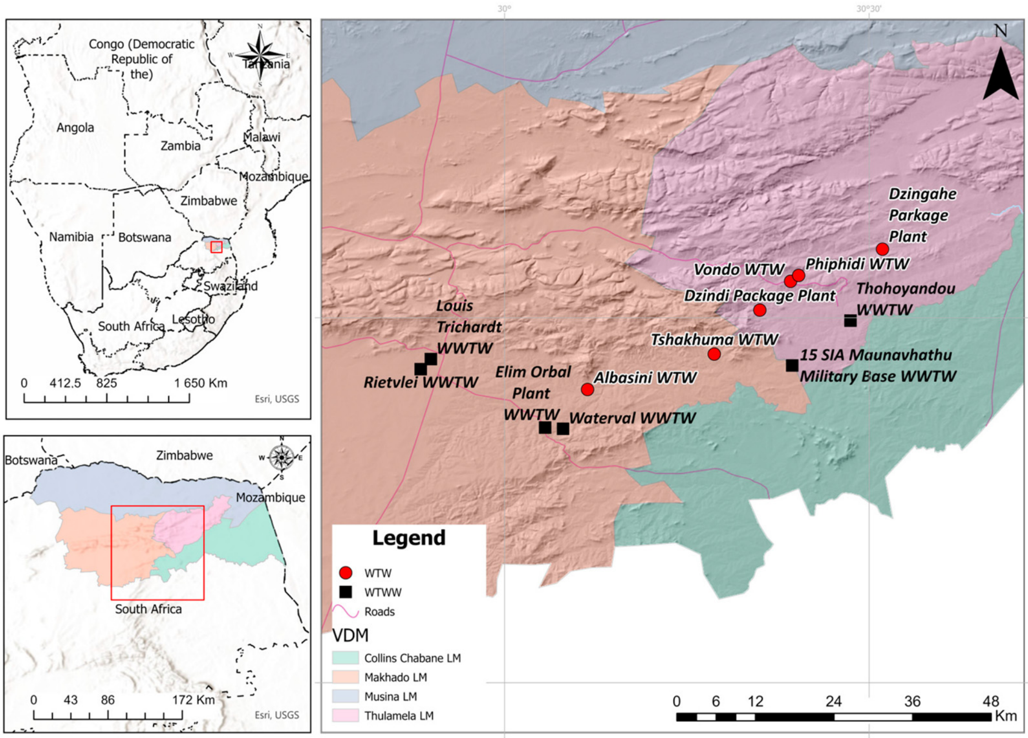

Figure 2. Location of the water and wastewater treatment plants that had workers surveyed for the current study within the Vhembe District Municipality, South Africa.

2.3. Sampling and Data Collection

The study employed a qualitative methodology that comprised semi-structured, in-depth interviews [33–35] to evaluate and investigate the viewpoints of workers regarding water and wastewater treatments and their educational backgrounds, as well as the preservation and conservation of water resources. Semi-structured interviews are interview guides that consist of open-ended questions and topics related to the study [36]. Interviews were conducted with 18 employees (water treatment works (WTW) n = 10; wastewater treatment (WWTW) n = 8), including supervisors, chief process controllers, and process controllers. Although the sample size of 18 workers is relatively small, it is appropriate given the qualitative nature of the study, which aims to provide in-depth insights rather than statistical analysis. Participants were selected based on their roles in the treatment plants, which puts them in a unique position to provide valuable information. The plant workers were interviewed for between 30 and 45 min during the day, either in English or TshiVenda. After conducting 18 interviews to fulfil the defined objectives, data saturation was reached because no new or relevant information surfaced [34].

2.4. Data Analysis

Thematic Analysis

The study used a thematic approach to analyze and interpret the data, which involved identifying themes or patterns in qualitative data. The goal of this approach was to find and apply key themes to understand the study or discuss a subject [37]. Ostrom's Institutional Analysis and Development (IAD) Framework was used in this study to deductively analyze the governance of water resources in water and wastewater treatment plants in the Vhembe District Municipality [26]. The IAD framework was used to identify relevant themes for analysis, providing a clear and comprehensive approach to address the study's objectives and discuss the findings in detail (Figure 1).

3. Results and Discussion

The findings of the semi-structured interviews that were done with the supervisors and process controllers from 12 water and wastewater treatment plants in the Vhembe District Municipality were grouped into five key research themes: (1) understanding of water/wastewater treatment system, (2) educational and demographic profile, (3) water quality assessments, (4) operational performance and regulatory compliance, and (5) water volume in waterworks plants. A thorough image of the existing condition of the treatment plants, staff perceptions, and institutional and operational challenges was created by categorizing the responses per these themes. Based on the themes and interview questions, particular codes were assigned to each response as part of the coding process. For instance, theme 1 (knowledge of water/wastewater treatment systems), participant 5, and question 24 are represented by the code T1/P5/Q1 (Table 2). This section was divided into five parts to analyze the findings according to the themes.

Using Ostrom's IAD approach, we can systematically investigate the institutional structures, laws, and community attributes that affect water management efficiency in the Vhembe District's water and wastewater treatment plants [26]. Several studies on local resource management employed Ostrom's IAD framework [27]. "Action arena" is the central component of the framework composed of actors and action situations [26,27]. In this study, water and wastewater treatment plants serve as the action arena, where various actors engage to manage water resources. Chief process controllers, supervisors, process controllers, and operators are among the key actors that have been identified. The action situation covers tasks including managing plant capacity, sourcing water, and purifying water to meet required standards (Figure 1).

Table 2. Interview questions administered to water and wastewater treatment employees.

Questions	Theme
Do you understand the current water or wastewater treatment system at your workplace?	1
What treatment methods do you use to treat water or wastewater?	1
What is your gender?	2
What is your age?	2
What is your education level?	2
What is your length of time in post (job)?	2
What is your post (job) or level?	2
What is your position within the company?	2
How long have you ever been with the company?	2
Are you satisfied with the standard of treated water at your plant? If no, what do you think needs to be improved?	3
Do you drink the water treated at your plant? Would you consider it to be safe to be released into the environment?	3
What is the quality of surface waters or wastewater that you treat in your organization?	3
Do you regard water quality as a problem?	3
Do have the treated water tested? What tests do you do?	3
Where do you get your water from that you treat? Do you think your plant has the sufficient capacity to meet everyday needs?	4
How much water/wastewater do you treat per day? If so wastewater treatment: how often do you break down? And what do you do to mitigate breakdown and ensure water released into the environment meets standards?	5

3.1. Theme 1: Understanding of Water/Wastewater Treatment System

The participants showed a strong understanding of the water and wastewater treatment systems at their workplaces. Several participants, mainly those holding supervisory roles, showed a thorough comprehension of the treatment procedures by naming techniques such as backwashing, activated sludge treatment, and rapid gravity sand filtration. This reflects the "rules-in-use" of Ostrom's framework within their organizational settings, indicating the established protocol and procedures governing treatment processes [26]. Ostrom's framework has been used in other research to examine different aspects of resource governance. Meinzen-Dick [38], for instance, employed it to examine water administration in India and showed how regional norms and rules significantly affect the success of water management practices. Cox et al. [39] demonstrated how institutional arrangement affects sustainability outcomes by applying the framework to forest management. Applying these frameworks to waste management, especially wastewater treatment, has important implications for South Africa. Standardized treatment processes and better water quality results are ensured by clear regulations and procedures, which also increase the efficacy and efficiency of wastewater treatment plants. In resource-constrained environments such as South Africa, where poor management can have a serious environmental and public health problems, this is important.

> *"We use rapid gravity sand filter."* (T1/P5/Q2)
>
> *"We do backwashing. . ."* (T1/P9/Q2)
>
> *"screen-removal 24 h/grits removal daily, desludging the sludge to drying beds daily and disinfecting final effluent 24 h. . ."* (T1/P14/Q2)

3.2. Theme 2: Educational and Demographic Profile

Participants displayed varying degrees of qualification, with other participants displaying the highest levels. The educational differences between the water management employees in the Vhembe district with no formal education and those with tertiary education emphasize important problems with human capital in efficient resource management. Historical and socioeconomic issues, such as the legacy of apartheid, which has affected access to high-quality education, and financial constraints that keep people from pursuing higher education, are at the basis of these inequities. The issue is, further, made worse by institutional obstacles, such as the scarcity and poor quality of training programs and hiring procedures that might not give priority to educational background. This is important because, as stated by Spellman [40] and Hrudey et al. [41], more education and training are associated with enhanced problem-solving abilities, technical knowledge, and adherence to safety and quality standards. According to Rivas et al. [42], the quality and quantity of water delivered in Africa are frequently insufficient because operators are unable to manage some of the complicated water technologies now in use. This is because there are insufficiently experienced operators and technicians [43].

"*. . . I am not educated. . .*" (T2/P2/Q4)

"*. . . I have grade 6. . .*" (T2/P13/Q4)

"*. . . I have (NQF level 7) BSc in Water and Sanitation. . .*" (T2/P17/Q4)

Access to education and training is made more difficult by intersectional factors such as gender and geographical location, which can provide additional challenges for women and those living in rural areas. This is grounded in Ostrom's framework ensuring that the community's attributes are effectively used to accomplish sustainable and efficient water management, which eventually improves operational effectiveness and adherence to water quality regulations [26]. Certain approaches can be taken to overcome these challenges, by drawing on empirical studies that have effectively applied Ostrom's framework. In Uganda, for example, Meinzen-Dick and Nkonya [44] emphasized the significance of local training programs that integrate gender-sensitive techniques and traditional knowledge. By making training available to women and people living in rural areas, these programs improved community engagement and compliance with water use restrictions. Pahl-Wostl et al. [45], also talked about adaptive management techniques in water governance, putting a focus on ongoing education and involving stakeholders to address challenging water management issues.

3.3. Theme 3: Water Quality Assessment

The analysis of attributes and methods used by the participants to assess the quality of the water in their treatment plants reveals several significant patterns and trends through their responses. Specifically, there is a lack of consistency in testing techniques among treatment plants, as seen by different testing methods that participants reported employing, including measuring turbidity, testing pH, and chlorine, and monitoring the levels of ammonia, nitrate, and chlorine, as shown in Table 3.

Table 3. Testing parameters in water and wastewater treatment plants (Vhembe district municipality).

Participant	**Water Quality Parameters**									
	pH	**Chlorine**	**Turbidity**	**Temperature**	**Electrical Conductivity**	**Coliforms**	**Nitrate**	**Ammonia**	**Chemical Oxygen Demand (COD)**	**Phosphate**
T3/P8/Q14	✓	✓	✓		✓					
T3/P10/Q14	✓	✓	✓							
T3/P11/Q14	✓	✓	✓							
T3/P13/Q14	✓	✓	✓							
T3/P15/Q14	✓	✓		✓		✓	✓	✓	✓	✓
T3/P18/Q14	✓	✓						✓	✓	

✓ represents the parameters that participants test in their treatment plants.

The responses showed a crucial problem with water quality monitoring where only chlorine is tested, and other tests are ignored. According to Ostrom's framework, regarding the importance of institutional arrangements and community attributes in resource management, effective governance requires well-established regulations that are constantly followed [46]. In South Africa, there are key institutions responsible for establishing and implementing water quality standards. Unfortunately, there are deficiencies in these regulations that reduce their efficacy. For instance, the National Water Act (36 of 1998) requires extensive water use licensing, but insufficient enforcement and administrative obstacles usually cause the process to be delayed [47]. Furthermore, even though the Water Services Act mandates that municipalities supply clean water, many treatment plants struggle with inadequate financing and poor infrastructure maintenance, which frequently results in water shortages and quality problems [48,49]. These regulatory deficiencies are made worse by insufficient resources for ongoing enforcement and monitoring as well as insufficient quality control procedures.

The lack of transparency and standardization in water quality monitoring methods is a serious problem that is demonstrated by this variability. However, the satisfaction of participants with achieving "recommended ranges" raises questions. The standards need to be clarified, as does whether they align with national drinking water standards (SANS 241:2015) [50]. The South African National Standard (SANS) 241:2015 [50] specifies that critical criteria for drinking water include pH values between 5 and 9.7, turbidity levels below 1 NTU, and chlorine residual levels between 0.2 and 0.5 mg/L. It is essential to check whether these standards include all required water quality measures and are updated often to address emerging contaminants. In the North West province, Gumbi [51] conducted a study that focused on several physicochemical parameters. The overall results for both research sites after the water treatment processes were consistent with the SANS 241 residential water quality criteria, except for the Mmabatho Water Treatment Plant's turbidity, electrical conductivity, total hardness, and calcium levels. The staff's educational and training backgrounds are closely related to the differences in testing methods and transparency, emphasizing the importance of human capital in Ostrom's framework for efficient water management.

> *"I am satisfied since we meet the provided standards. That standard is within recommended ranges"* (T3/P17/Q10)

Participants expressed that they do consume the water treated at their plants, suggesting a certain degree of confidence in the safety and purity of the treated water. This shows that they are satisfied in the efficiency of their quality control and water treatment procedures. It also takes into account the practical aspects of their workplace, where drinking treated water might be the easiest or most convenient way for them to stay hydrated throughout their shifts.

> *"We do drink the water. We also do have a tap in the plant"* (T3/P1/Q11)

> *"We do drink the water in the plant. The water is very safe because we are releasing it into the households"* (T3/P2/Q11)

Five participants disclosed that they avoid consuming water from their plants due to their recognition of them as wastewater treatment plants but the water only being safe to be released into the environment. This offers significant insights into their understanding of the facility's purposes and their perspectives on water safety.

> *"Water is not safe to drink but to the environment is safe"* (T3/P12/Q11)

> *"It is a wastewater, so we do not drink water from here"* (T3/P15/Q11)

One participant has mentioned that since the plant is for wastewater treatment, they are being provided with water tankers for drinking water.

"We had a borehole, but it has broken due to load-shedding. Now we are being provided with water tankers" (T3/P17/Q11)

Two participants identified wastewater treatment works at Dzindi and military houses as sources of contaminated water that enter the natural environment. This shows that there are pollutants in the sources which could compromise water quality and require efficient treatment methods to ensure human and environmental health safety.

"Contaminated water from the Dzindi River" (T3/P3/Q12)

"Contaminated water from military houses" (T3/P18/Q12)

3.3.1. Sub-Theme 3.1: Meeting River Quality Standards

According to the responses, the wastewater the plants treat meets river quality standards, indicating a dedication to protecting and preserving water resources. This also shows that treatment procedures aim to meet quality requirements for surface water. Following these guidelines shows that the plants prioritize the health of the water bodies downstream in addition to adhering to environmental requirements. Wastewater treatment plants help to preserve the area's water resources and lessen the possibility of harmful consequences from wastewater discharge by treating wastewater to these criteria. The dedication to fulfilling river quality criteria is outstanding, but it is crucial to monitor and evaluate how well these treatment methods are working. It is essential to guarantee the constant efficacy of treatment procedures and to adjust them in response to modifications in water quality standards or new contaminants.

"The water is treated to the standard of river quality" (T3/P15/Q10)

3.3.2. Sub-Theme 3.2: Impact of Load Shedding on Water Quality

One participant indicated that during load shedding, water quality declines, especially at stage 6, when the treatment process is stopped. This emphasizes how susceptible water treatment plants are to power outages and how important backup measures are. Wastewater treatment is one of the industrial processes that uses the most energy, accounting for approximately 1% of the energy consumed in Europe and 4% of that consumed in the USA [51,52]. The introduction of restrictive standards for the quality of water effluents has led to a significant increase in the energy demand for this process, requiring the use of advanced technologies to remove pollutants [51,52]. South Africa, like other countries in Southern Africa, is undergoing a severe energy crisis that frequently results in regular power outages. As a result, load-shedding is implemented to control electricity consumption and avert grid failure [53–55]. To balance supply and demand, load-shedding has been enforced in phases 1 through 8 by Eskom, the primary electricity provider in the country [53]. According to Vrzala et al. [56], the quality of wastewater discharged and non-compliance with discharge limitations can occur from prolonged power outages, which indicate a reliance of wastewater treatment plants on electrical supply. In certain WWTPs, wastewater may be emergency discharged within 6–8 h to a recipient (often a river) in the event of a power failure. If there is a lot of rain at this time, the discharge will happen right away [56].

". . .The water quality is good though, during load-shedding stage 6, the quality deteriorates because the process stops" (T3/P17/Q10)

3.3.3. Sub-Theme 3.3: Perceptions and Impacts of Water Quality Issues

There are differing opinions about whether water quality is considered a problem, according to the responses given. One respondent made it clear that there is a problem with the quality of the water, especially in rivers where people are swimming in contaminated water. Numerous waterborne illnesses, including cholera, typhoid fever, shigellosis, salmonellosis, campylobacteriosis, giardiasis, cryptosporidiosis, and viral infections causing hepatitis A, can be spread by contaminated water [57]. These have impacts on the socioeconomic and healthcare sectors, including a significant level of morbidity and death in various age groups [57]. This suggests that people are aware of the problems with water contamination and are worried about how it may affect the local community's health. The answer implies that the respondent does consider the water quality to be an issue.

> "*. . . Yes, there is a water quality problem, especially in rivers. People are swimming in polluted water*" (T3/P2/Q13).

On the other hand, several participants stated that they do not consider water quality to be an issue. It is critical to understand the motivations underlying this belief. It may result from a lack of knowledge or worry about possible problems with water pollution. A participant brought up operational difficulties with chlorine disinfection, pointing out situations in which they are short of chlorine, which impacts water quality. This emphasizes the difficulties in successfully managing water treatment procedures, which might affect water quality, even though it does not directly address whether or not water quality is seen as a concern.

> "*. . . Yes, sometimes they don't give us chlorine to disinfect and that affects quality*" (T3/P15/Q13)

3.4. Theme 4: Operational Performance and Regulatory Compliance

The participants indicated that they obtain their water for treatment from different sources. One respondent stated that the Albasini reservoir provides them with water, but they are concerned that the plant's capacity is insufficient to fulfil their daily requirements. Despite the country's constitution that states that everyone has the right to clean and safe drinking water, millions of South Africans do not have sustained access to a source of drinkable water [18,58].

> "*Albasini Dam. No, our plant does not have sufficient capacity to meet everyday needs*" (T4/P5/Q15)

Other respondents stated that the plants do not have enough capacity and identified the Phiphidi Dam and Vondo Dam as their water sources.

> "*. . . Vondo Dam and not sufficient. . .*" (T4/P9/Q15)

> "*. . . Phiphidi Dam and No. . .*" (T4/P10/Q15)

According to a study by Khabo-Mmekoa et al. [59], the Ugu District of South Africa supplies water to both rural and urban areas through the same treatment plant. However, urban areas benefit from direct tap access in their homes, while rural areas rely on standpipes and household containers for water collection. This demonstrates a clear disparity in water service access between urban and rural areas in South Africa. Small water treatment plants, which are described as water treatment systems constructed in poorly serviced areas that typically do not fall inside the borders of urban areas, are typically used to supply water to rural [57]. Among them are boreholes that supply water to rural clinics, schools, hospitals, and forestry stations [18,60]. However, several technical and managerial issues hinder the effectiveness of small water treatment plants [57]. These issues include the incapacity of plant managers to perform basic equipment repairs or to calculate chlorine dosages, flow rates, and free chlorine residual concentration estimations [57]. The detection of *E. coli* in the water boreholes utilized at the local clinics, as reported by Edokpayi et al. [18], suggests that patients are at risk of re-infection whilst admitted.

The effectiveness and sustainability of water treatment systems are severely affected by the operational compliance in municipal water treatment management. Some participants expressed concerns about challenges including equipment failures, financial limitations, load-shedding and restricted resource accessibility, which may affect the supply of water to the communities. According to the Water Research Commission [61], inadequate infrastructure investment over the previous 20 years, management, and planning were the main causes of these losses. As stated by Adams et al. [6], state-controlled water supplies run by public water companies face challenges like corruption and inefficient administration, which makes financial constraints even worse. Another major worry raised by participants is maintenance, with many calling for quicker repairs to avoid recurring equipment failures. The Water Research Commission [61] has highlighted the recurrent environmental and public health crises caused by inadequate management techniques and delayed maintenance. According to Murei et al. [12], insufficient infrastructure hinders treatment plants from efficiently managing the wastewater load, and treatment plant functioning directly affects the plants' ability to provide water to communities. Institutional arrangements increase these operational inefficiencies. According to Haldar et al. [62], the development of efficient wastewater management systems is made difficult by unclear institutional arrangements and inadequate coordination between national and local organizations.

> *"No, the dosing pumps are not functioning well, we only test chlorine and others are not tested. The filter pump is only one, so the provision of a filter pump should improve. Loadshedding is affecting us. Safety during load-shedding"* (T4/P1/Q15)

> *"Yes, there are challenges with water leakages. The municipality should quickly fix all machines"* (T4/P2/Q15)

> *"No, some of the machines are not working such as lime feeder, dry beds and the plant is not maintained"* (T4/P18/Q15)

3.5. Theme 5: Water Volume in Waterworks Plants

The responses given on the volume of water and/or wastewater processed daily shed important light on the size of the treatment plants' activities. One respondent indicated that they were treating 10.36 megaliters (mL/day). Another participant disclosed that they treat 43 mL of water every day. Furthermore, one responder reported treating 13 megaliters each day, and another indicated treating 0.8 megaliters per day. Despite water from Albasini reservoir, Mutshindudi River, Vondo reservoir, Phiphidi reservoir, and other nearby sources, the biophysical conditions [26] differ between the plants. There are significant variations in resources and capabilities between the treatment capacities, which vary from 0.8 mL/day to 43 mL/day. The plants' capacity to meet their daily water needs and maintain treatment standards is directly impacted by these conditions.

> *"…10.36 megaliters per day (mL/day)…"* (T5/P5/Q16)

> *"…43 megaliters per day…"* (T5/P9/Q16)

> *"…13 mL/day…"* (T5/P10/Q16)

> *"…0.8 mL/day…"* (T5/P14/Q16)

One participant expressed uncertainty regarding the amount of water they treat daily due to malfunctioning flow meters, suggesting a possible problem with the monitoring and measurement apparatus. As it comes to breakdowns, the respondent suggested taking a reactive strategy by contacting mechanics and electricians as problems arise. Another participant brought up phoning engineering when a breakdown occurs.

> *"I am not sure, in and out flow meters not working. When there is a breakdown, we call the electrician and mechanics…"* (T5/P11/Q16)

> *"Report to engineering…"* (T5/P8/Q16)

One of the key management issues identified by Meme [63] was the failure to maintain equipment. According to Momba and Thompson [57], the lack of routine maintenance was mentioned by around 60% of the small water treatment plants (SWTPs) operators interviewed in all the provinces, including the Eastern Cape, Free State, Western Cape, Mpumalanga, and Limpopo Provinces. In the study conducted in the Greater Giyani Local Municipality, households and public institutions in the area struggle daily to obtain water since municipal pipes and boreholes are insufficient to supply enough water for the entire community [64]. The finding from Mmbadi [64] is strongly linked to this study's investigation into resource management and water governance in the Vhembe District Municipality and is strongly linked to this study's finding. The Vhembe District Municipality faces difficulties with water scarcity and irregular water supply, which are comparable to those in Greater Giyani. This emphasizes the significance of efficient institutional arrangements and governance, as examined by Ostrom's Institutional Analysis and Development (IAD) Framework.

The responses suggest that there are differences in the capacity and source of water amongst treatment plants. Concerns over infrastructure sufficiency to meet water treatment demands are raised by the capacity problems described. To guarantee the efficient and long-term functioning of water treatment plants, this insight emphasizes how crucial it is to evaluate and resolve capacity constraints.

Table 4 provides an analysis of the problems with water management that different countries (South Africa, Ethiopia, India, Pakistan, Malaysia, China, Libya, and Brazil) are facing. The institutional arrangements show a pattern of unclear responsibilities, inadequate coordination, and problems with governance that limit efficient water management in these areas. In Ethiopia, Pakistan, and the Vhembe District, for example, there is a lack of institutional capacity and inadequate coordination, while Brazil has multiple agencies and complicated administrative challenges.

The operational challenges that are common in Vhembe District, as well as in Ethiopia and Malaysia, include breakdowns of equipment, insufficient capacity, and limited budgetary resources. Key obstacles include insufficient financial and technical resources as well as an ineffective management strategy, particularly in public facilities. Brazil is one example of this, where ineffective planning and operational skills worsen water management problems.

Significant challenges arise from compliance issues as well, especially in the Vhembe District where regulatory monitoring and water quality testing are inconsistent, while in Brazil, standards are stricter yet unworkable. These countries' operational inefficiencies are a result of social and political problems, such as poor public engagement and insufficient awareness of water and wastewater treatment. The declining water quality in the Vhembe district, as well as improper wastewater management and waterborne illnesses observed in countries such as China, are among the environmental concerns raised.

Table 4. Comparison of institutional and operational challenges in water management studies.

Parameter	**Current Study (Vhembe District Municipality)**	**Ethiopia** [65]	**India** [66]	**Pakistan** [67]	**Malaysia** [68]	**China** [69]	**Libya** [70]	**Brazil** [71]
Institutional arrangement	Unclear roles, poor coordination between stakeholders	Weak institutional coordination	Confusion and hesitation amongst sectoral stakeholders, deficits in institutional capacity	Absence of institutional responsibility, governance malfunctions	Weaknesses in water management	Inappropriate governance	Poor government plans	Complex bureaucracy with multiple agencies and bureaucratic levels hindering wastewater management processes
Operational challenges	Equipment breakdowns, load-shedding insufficient capacity, limited financial resources	Limited human resources, insufficient financial resources			Lack of capacity	Financial unsustainability, technical challenges	Inefficiencies of treatment plants, drainage networks not in good standard	Limited planning, insufficient technical and managerial capacity, and lack of operational skills in public utilities
Compliance issues	Inconsistent water quality testing, lack of regulatory oversight		Inadequate monitoring, insufficient risk assessment, frequent changes and inconsistencies in water standards					Strict de jure legislation complicates practical implementation; regulations often do not reflect operational realities
Social and political issues	Low public engagement, limited awareness of water management		Lack of awareness of the wastewater risks					Low connection rates to public sewerage are socially problematic, sewage becoming a higher political priority but still competing with other public concerns
Environmental concerns	Deteriorating water quality						Mismanaged wastewater, water-borne diseases	Water scarcity pressures showing the need for wastewater reuse, but reuse potential remains untapped

4. Conclusions

The findings show the significant operational, environmental and institutional challenges faced by water and wastewater treatment plants. The key issues such as load-shedding, inadequate maintenance, and equipment breakdowns result in treatment facilities not functioning properly. It was observed that workers are knowledgeable about treatment procedures; however, institutional issues like insufficient resources and poor institutional support affect the effective functioning of treatment plants. These challenges do not only threaten water quality but also pose risks to public health and environmental sustainability. To address these complex challenges, this study emphasizes the importance of strengthening institutional arrangements, investing in infrastructure upgrades, adopting proactive management practices, improving maintenance plans, enforcing strict regulatory oversight to ensure that water quality regulations are adhered to, and implementing training programs for all workers. The application of Ostrom's IAD frameworks offers a strategic approach to managing these challenges by promoting effective monitoring, stakeholder engagement, and clearly defined responsibilities. Municipalities should prioritize establishing strong governance frameworks, encouraging local stakeholders to participate in decision-making, and ensuring the resources are available. Additionally, using local talent through targeted recruitment and training programs, including internships and apprenticeships for young professionals, can close skills gaps and improve operational capacity. For broader application, the findings can serve as a guide to other sub-Saharan African countries facing similar institutional arrangements breakdowns and water management challenges. Future research should explore cross-regional collaborations to share best practices and develop solutions that enhance water security and environmental sustainability. By integrating these into policy and practice, municipalities can improve the operational efficiency of their water treatment facilities, preserve water quality, and ensure sustainable access to clean water for all communities.

Recommendation for Future Works

Workers from water and wastewater treatment plants should receive training regarding new technologies that are used in treatment facilities. Stakeholders should visit water and wastewater treatment plants frequently to assess whether regulations are being followed and if the plants are being managed appropriately. Renewable energy should be installed as a backup during load-shedding in water and wastewater treatment plants; this will stop wastewater that does not meet standards from being discharged and since renewable energy is environmentally friendly. To keep water and wastewater treatment plants operating efficiently, machinery should be regularly inspected and maintained, and water testing instruments should also be serviced and calibrated to meet the standards. Furthermore, the government should allocate additional funds to these plants to ensure the proper operation of water and wastewater treatment plants. Criteria for drinking water should be periodically revised against WHO criteria.

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