A DEMONSTRATION OF TREATMENT TECHNOLOGIES FOR DIRECT POTABLE REUSE

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A DEMONSTRATION OF TREATMENT TECHNOLOGIES FOR DIRECT POTABLE REUSE

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

BACKGROUND

Water scarcity is a global challenge, affecting millions of people, industries, and ecosystems. The United Nations predicts that by 2025, half of the world's population will live in water-stressed areas. The world faces severe water shortages due to prolonged droughts and climate change. The demand for water exceeds the available supply, and traditional water sources, such as rivers, lakes, and groundwater are becoming increasingly depleted and polluted. South Africa is a water-scarce country, with an average annual rainfall of less than 500 mm per year. The country faces increasing water stress due to prolonged droughts, climate change, and population growth. According to the National Water Resource Strategy, South Africa is projected to experience a water deficit of 17% by 2030, which could affect economic growth, food security, and public health. The Western Cape Province, which includes the city of Cape Town, is particularly vulnerable to water scarcity due to its semi-arid climate, high population density, and dependence on surface water resources.

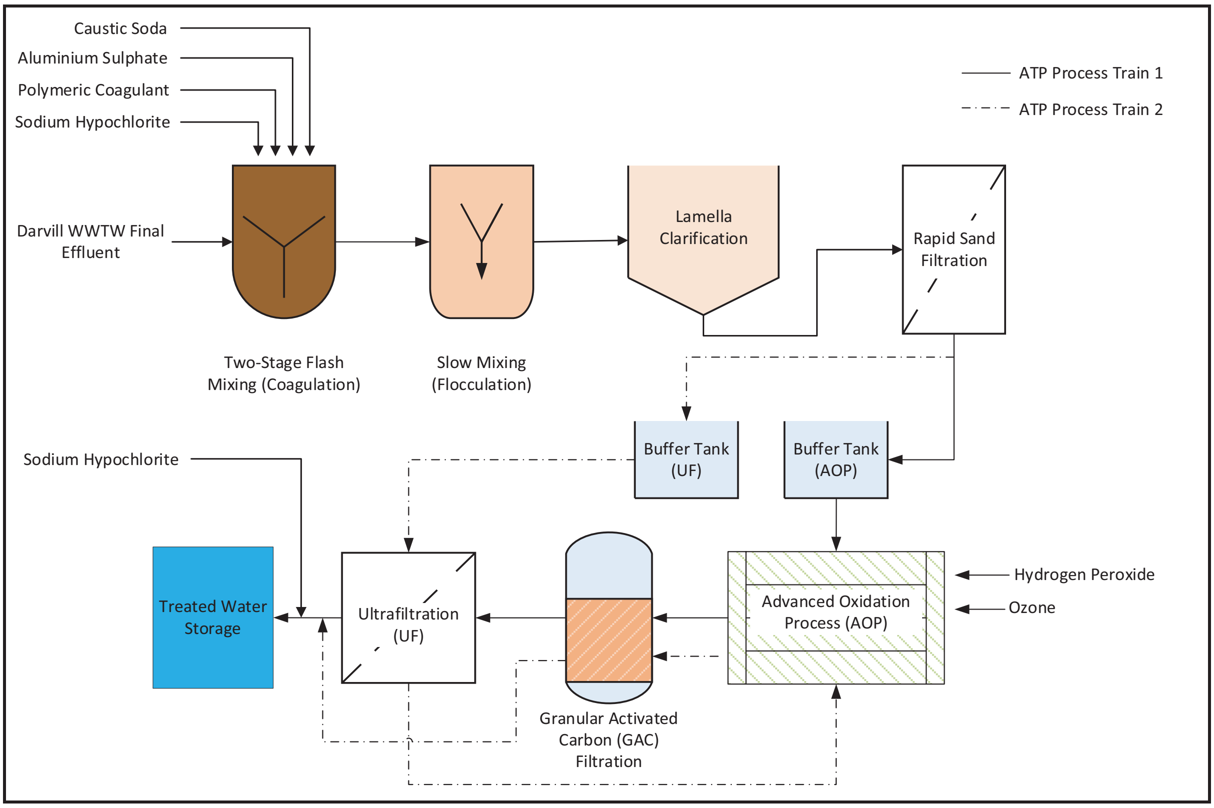
One solution to address water scarcity and stress is to reuse wastewater, particularly for non-potable uses such as irrigation, industrial processes and toilet flushing. However, the reuse of wastewater for drinking purposes, known as 'direct potable reuse', is still relatively new in South Africa and faces technical, economic, and social barriers. Direct Potable Reuse (DPR) involves treating wastewater to a high standard that meets drinking water quality regulations and distributing it directly into the drinking water system. uMngeni-uThukela Water has completed a number of research projects on water reuse, and these have provided valuable information on the process technology selections for a direct potable reuse plant. Metcalf *et al*. (2014) conducted a study, funded by the Water Research Commission, on wastewater reclamation for potable reuse. The final report was published in two volumes: Volume 1 (WRC report no. 1894/1/14) reported on "Evaluation of Membrane Bioreactor (MBR) Technology for Pre-Treatment" and Volume 2 (WRC Report No. 1894/2/14) reported on "The Integration of MBR Technology with Advanced Treatment Processes".

The authors investigated several membrane types and applications at a bench and pilot-scale. The researchers evaluated several options which included MBR, nanofiltration (NF), reverse osmosis (RO) and combinations of membranes in series. In addition, the combination of ozonation (O_3) with granular activated carbon (GAC) and an advanced oxidation process (AOP) by combining ultra violet (UV) radiation with hydrogen peroxide were also evaluated. The project findings were that membrane and carbon processes combined with ozonation are capable of reducing concentrations of emerging contaminants; however, some compounds were also detectable in the membrane permeate and GAC effluent. AOP was very effective in removing steroid hormones as well as providing an additional barrier to pathogens.

The study concluded that if reclamation is considered to be feasible at Darvill Wastewater Treatment Works (WWTW) and other wastewater works in the interior, an alternative treatment train such as MBR-O_3-GAC-UF-UV will have to be considered. This study by Metcalf *et al.* (2014) formed the design basis for the treatment process selection of the Final Effluent Reuse Demonstration Plant (FERDP) at Darvill WWTW. The site is located in Pietermaritzburg and is undergoing an upgrade of its treatment capacity from 65 to 120 ML/d. Following the outcomes of WRC Project No. K5/1894, uMngeni-uThukela Water provided the engineering consultant, Hatch, with a process design basis and requested the engineering design team to proceed with the design of a tertiary treatment plant for the Darvill WWTW Upgrade project. As part of this upgrade, the 2 ML/d FERDP was installed as the sole potable water source for all Darvill WWTW process requirements as well as to serve as a demonstration plant for the public.

The 2 ML/d FERDP receives treated effluent directly from Darvill WWTW and consists of a conventional treatment plant (also referred to as a 'High Pressure' Wash plant) followed by an advanced water treatment plant (ATP). The conventional process includes coagulation, flocculation, lamella clarification and rapid gravity filtration. The ATP consists of ultrafiltration (UF), advanced oxidation process (AOP) with hydrogen peroxide and ozone, granular activated carbon (GAC) filtration and onsite electrolytic chlorination (OSEC) for

disinfection of the final water. The ATP has two process configurations. In process configuration No. 1, the filtered water from the conventional water treatment process (i.e. feed water to ATP) undergoes advanced oxidation followed by GAC filtration, UF and OSEC. In process configuration No. 2, the feed water is pumped to the UF membranes followed by advanced oxidation, GAC filtration and OSEC.



Process Flow Diagram of the Darvill Final Effluent Reuse Demonstration Plant

The main expectation from this study was research for the future implementation of direct reuse as a sustainable potable water source in South Africa, with full public support for the technology, operational, maintenance and monitoring effectiveness, and the final water quality. The implementation of DPR plants reduces the demand on conventional water treatment plants. Other positive impacts of this project include the development of extensive process expertise in selecting appropriate treatment technologies and operating conditions for the removal of microorganisms and emerging contaminants. Contaminants of emerging concern (CECs) are substances, such as pharmaceuticals, pesticides and personal care products, that are a potential risk to human and environmental health. The research was conducted at the Final Effluent Reuse Demonstration Plant (FERDP) at uMngeni-uThukela Water's Darvill Wastewater Treatment Works (WWTW) located in Pietermaritzburg, South Africa. This plant was recently constructed as part of a project to upgrade the Darvill WWTW; therefore, this research study was impacted by the construction and commissioning schedule.

AIMS OF THE PROJECT

The following were the aims of the project:

1. To investigate the effectiveness of the treatment processes for the removal of microorganisms as well as selected contaminants of emerging concerns (CECs) from the plant influent.
2. To optimise the treatment unit processes for each of the selected process configurations for the removal of the selected microbial contaminants and CECs.
3. To assess the overall lifecycle costs and make recommendations for the implementation of a full scale direct potable reuse plant.

4. To develop practical operational and maintenance, water quality monitoring and public engagement plans for a direct potable reuse plant.

SCOPE OF WORK AND MAIN FINDINGS

1. Installation and commissioning of the demonstration plant

The research study faced a number of challenges due to its link to the main project of the Darvill WWTW Upgrade. External factors that contributed to the delays in the installation and commissioning of the FERDP included the COVID-19 pandemic and the change of main project contractors. Load shedding was also a factor that caused delays during commissioning and loss of production during operation. Once the plant was complete, Client operators were trained by the sub-contractor on start-up, operational and shutdown procedures for the advanced treatment units at the FERDP. The Client operators worked 12-hour rotational shifts during the hot (wet) commissioning of the plant and noted snags for the Contractor’s action. Plant operation and maintenance protocols were developed from the experience of operating the FERDP. The plant has been operated for a period of one year, however due to issues mentioned above, the operation has been intermittent.

2. Development and implementation of water reuse safety plan

A water reuse risk safety plan (WRSP) was developed using the principles and guidelines from other risk management approaches such as water safety planning, Hazard and Operability Study (HAZOP) and Hazard Analysis & Critical Control Points (HACCP). Safety and sustainability of the treatment system were prioritized by this plan, with the aim of mitigating potential health and environmental risks. Various hazards throughout the system, from catchment to distribution, were identified and addressed, with an emphasis on the importance of preventive measures and ongoing monitoring. The plan’s focus on identifying and monitoring targeted CEC and stringent control measures ensures a proactive approach to water quality safeguarding. Similarly, effective management practices were established to ensure the WRSP is implemented as planned and that any issues or concerns are identified and addressed in a timely manner. To this end, relevant documentation such as Standard Operating Procedures (SOPs) and transparent communication channels with stakeholders were developed to further enhance the facility’s operational safety and public confidence. Furthermore, a continuous review and updating strategy was established within the WRSP to ensure its flexibility in adapting to shifting conditions and emerging challenges.

The WRSP represents a proactive approach to ensuring the safe and sustainable operation of the water reuse treatment system. It assesses potential hazards, identified key risk factors, and helps implement control measures to mitigate risks to the environment and public health. It considers not only the FERDP, but also the catchment as well as Darvill WWTP. The implementation of effective management and communication strategies as per the plan, along with a dedicated commitment of the WRSP team to continual review and enhancement, plays a crucial role in the success of this plan.

3. Analysis of Contaminants of Emerging Concern (CEC)

To conduct the CEC analysis, three sets of samples were collected once the FERDP plant was operational. Grab samples of 200 mL each were taken in triplicate, before and after each unit operation of the plant. Furthermore, a composite sample of the influent, collected over 24 hours, was obtained. The collected samples were transported to the laboratory and processed within 48 hours. A 100 mL of each sample was decanted into a clean sampling bottle, to which an internal standard (26 µL) was added. These prepared samples were then transferred onto solid-phase extraction (SPE) cartridges (HLB, 6 cc, 200 mg). SPE cartridges underwent rinsing with 10 mL of ultrapure water, and were subsequently allowed to dry for 30 minutes under reduced pressure. The SPE cartridges were shipped to Umea University in Sweden for analysis. Liquid Chromatography with tandem mass spectrometry was used for analysis of extracts by Reversed-Phase Liquid Chromatography, followed by ionisation of the analytes with Heated Electrospray Ionisation in positive polarity mode and mass spectrometric (MS) detection with a triple quadrupole MS/MS system.

The FERDP consists of two process configurations. Process configuration No. 1 was operated and all required information relating to the unit processes were monitored and recorded. This includes water quality at each point of the process – where specific determinants were recorded every two hours, and samples were tested weekly for compliance to SANS 241: 2015 Standard for Drinking Water. Maintenance and operability issues were also noted, which are included in the Operation and Maintenance Manuals. Chemical dosing was also optimised, based on the water quality achieved.

Plant performance testing commenced during Stage 4 of the commissioning at FERDP. This stage is the final preparation for plant operation with final treated effluent from Darvill WWTW and required dosing chemicals. As a result of downtime of certain process units, the plant performance and water quality was only assessed for the following three process configurations:

1. HP Wash plant only (ATP bypassed);
2. HP Wash plant followed by ATP process configuration No. 1 (AOP > GAC > UF > OSEC); and
3. HP Wash plant followed by UF (AOP and GAC bypassed).

Client operators conducted two-hourly monitoring of turbidity concentrations at various sample points within the FERDP. Additionally, daily laboratory analysis of influent and final water samples were conducted to test for pH, colour, conductivity, suspended solids, chemical oxygen demand, total organic carbon, *E. coli*, alkalinity, calcium, ammonia, aluminium, iron, manganese, and nitrates. Full SANS 241: 2015 analysis was conducted on a weekly basis. However, due to limitations in the operation of the plant further performance testing and water quality monitoring would be required to confirm these results before publication.

The study focused on the removal of targeted CECs yielded promising results. The study identified a wide range of pharmaceuticals in the treated effluent. These include antiviral drugs, antibiotics, statins, antihistamines, antihypertensive/cardiovascular drugs, anticonvulsants and benzodiazepines. The multibarrier system demonstrated effectiveness in eliminating most of the targeted CECs, showcasing its capability for comprehensive contaminant removal. However, to draw more robust and definitive conclusions, further data collection is necessary. Continuous sampling, detailed analysis, and thorough evaluation of the existing treatment technology are essential to ensure a comprehensive assessment of the treatment process. Therefore, ongoing efforts will be maintained to gather additional data.

4. Life Cycle Costing Analysis

A preliminary life cycle costing Analysis (LCCA) for the Darvill Final Effluent Reuse Demonstration Plant was done to provide a holistic view of the costs associated with a DPR plant over its entire life span. This included the complete operating and maintenance costs that include power consumption, chemical usage, disposal, laboratory services/consumables and replacement of major equipment. The LCCA was conducted using the Net Present Value (NPV) method, an approach that requires all future cash flows to be converted to baseline, taking into account inflation.

The ultimate goal of conducting a life cycle costing analysis (LCCA) for the Darvill FERDP was to provide uMngeni-uThukela Water with a holistic view of the costs associated with a DPR plant over its lifespan, enabling the water utility to make informed decisions regarding its feasibility and long-term viability. The results showed a total project life cycle cost of ZAR155 million, based on a 20-year economic life. However, this result was based on several assumptions and estimations for operational expenditure (electricity, chemicals, laboratory services, human resources and maintenance) due to no availability of actual plant data. A simple sensitivity analysis concluded that the discount rate was the key driver for the LCCA. It is recommended that detailed sensitivity and scenario analyses be conducted on actual plant data. In order to establish the true cost effectiveness of the water reuse process implemented Darvill FERDP, a detailed life cycle costing analysis must be conducted once the plant challenges are addressed and comprehensive actual data can be captured over a 6 to 12 month operating period of the plant.

5. **Operational and Maintenance Aspects**

Water reuse is relatively new in the South African context and operating the Darvill FERDP provided the opportunity for the bulk water supplier to gain experience operating a treatment plant with advanced technology systems such as the AOP and UF system. Based on the extensive practical knowledge gained, an Operational and Maintenance protocol was developed, for municipalities, water suppliers and other stakeholders who may want to implement water reuse projects. Operators should have experience operating water and wastewater treatment plants, and additional, advanced training is required for the advanced treatment processes. Operators should possess effective communication skills, data recording skills and be computer literate amongst other competencies. Safety training is an important component of operation since chemicals such as ozone, citric acid, sulphuric acid and hydrogen peroxide are not used on conventional water treatment plants and require careful handling to avoid dangerous exposure or injury. Maintenance of the FERDP ensures that the plant will operate efficiently and preserve the life of the equipment. Planned maintenance on common equipment such as pumps, mixers, blowers and compressors can be done by the plant maintenance team according to the plant maintenance schedule. Complex units such as the ozone generator and ultrafiltration system requires a technician with specialised expertise such as the supplier for maintenance and repairs and this needs to be planned ahead to avoid downtime.

6. **Public Engagement and Knowledge Dissemination**

Public participation was important to address the concerns and perceptions associated with direct potable reuse. It involves the identification of the stakeholders that are impacted by the water reuse process and utilising methods to enable the water provider to obtain acceptance of direct potable reuse. The activities comprised of presentations at National Forums in 2019, 2020 and 2021. The questionnaires that were completed at the forums showed that majority of respondents understood the concept of water reclamation however, most were keen on it being used for industrial purposes as opposed to drinking water and household use. This indicates that more needs to be done to gain public acceptance of reclaimed water for drinking water purposes. There were also national and international conferences, plant tours, demonstrations and site engagements with many different stakeholders at all levels. This was successful as buy-in was obtained for the Darvill FERDP from the various stakeholders and collaborative projects with other municipalities and academic institutions have stemmed from the FERDP project.

7. **Capacity building**

Capacity building was also a significant component of knowledge dissemination and this was done by supporting postgraduate students with studies related to the water and wastewater industry. A Masters research project as well as two PhD studies were based on the operation of Darvill FERDP. Training of uMngeni-uThukela Water's process technicians, graduate trainees and in-service trainees to operate and optimise the FERDP provides invaluable experience and exposure to new technologies. A public engagement protocol was developed to provide guidance to any entity that plans to implement direct potable reuse.

CONCLUSIONS

In conclusion, the global challenge of water scarcity, coupled with the pressing issues of climate change and population growth, underscores the critical importance of innovative water management solutions. The project has shown that direct potable reuse, using different advanced unit treatment processes, has the ability to produce safe drinking water. However, challenges such as lack of in-house CEC analysis capability, load shedding, delays in installation and commissioning, limited operator skills and external factors need to be addressed to ensure the smooth operation of this plant and similar plants.

Various challenges related to project delays and intermittent operation were encountered, comparison of the different process trains were not able to be carried out fully. However the FERDP demonstrated promising results in producing potable quality water that meets SANS 241:2015 standards. The results so far also provide valuable information on the removal efficiency of various CECs in the wastewater treatment process, which is essential for the safe reuse of treated wastewater as a source of potable water. The data can also be used by policymakers and regulatory bodies to establish guidelines and regulations for the safe discharge of treated wastewater into the environment. Additionally, an LCCA provided insights into the economic aspects of DPR implementation, with the discount rate identified as a key influencing factor.

The project has also highlighted the importance of public participation and capacity building in addressing concerns and perceptions associated with direct potable reuse. Despite the challenges, the project has provided valuable experience for the bulk water supplier (uMngeni-uThukela Water) to operate the FERDP and develop water reuse plant protocols for other municipalities and water suppliers that wish to implement direct potable reuse.

RECOMMENDATIONS

This research project has demonstrated the feasibility of using these advanced treatment technologies for direct potable reuse, further research and development in the field is required. Additional research can be conducted into the effectiveness of various process configurations utilising AOP, GAC and UF. DPR demonstration plants provide a unique opportunity to test and evaluate the advanced water treatment technologies and processes.

The plant's overall performance can be enhanced by pursuing further optimisation measures, investing in human resource development and fostering consistent public engagement to improve acceptance and fully harness its potential. Continuous detection and monitoring of CECs are recommended, along with expanding the list of targeted CECs to include a broader range of contaminants. Additionally, developing in-house analytical methods and capacity is crucial.

It is necessary to also develop and implement regulatory frameworks for reuse systems. Life cycle costing was conducted for this study, however it is recommended that further research be undertaken with detailed data for accurate analysis. Ensuring public acceptance is vital for the success of a direct reuse plant, and knowledge dissemination through various means should be conducted to improve the public’s perception of direct reuse. The current WRSP, developed by the UUW team, could benefit from involving external stakeholders like regulatory authorities, and the public. Their inclusion would provide additional perspectives and strengthen the WRSP.

The South African water reuse sector still in its early stages of development, but it is expected to grow in importance as the country faces increasing water scarcity challenges. It is therefore recommended that the WRC, utility companies such as UUW, and other relevant organizations continue their collaborative efforts.

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS & ABBREVIATIONS

AOP	Advanced oxidation process
ASME	American Society of Mechanical Engineers
ATP	Advanced treatment plant
BPA	Bisphenol-A
CCP	Critical control point
CEC	Contaminants of Emerging Concern
CIP	Clean-In-Place
COD	Chemical oxygen demand
CSIR	Council for Scientific & Industrial Research
DPR	Direct Potable Reuse
DSI	Department of Science and Innovation
DWS	Department of Water and Sanitation
ENM	Engineered nanomaterial
EPA	Environmental Protection Agency
FAT	Factory Acceptance Testing
FDS	Functional design specification
FERDP	Final Effluent Reuse Demonstration Plant
GAC	Granular activated carbon
HACCP	Hazard Analysis and Critical Control Point
HAZOP	Hazard and Operability
HMI	Human-Machine Interface
HP	High pressure
IMP	Incident Management Protocol
ISO	Internation Organization for Standardization
LCA	Life cycle assessment
LCCA	Life cycle costing analysis
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LMH	Litres per meter squared per hour
LOQ	Limit of quantification
MBR	Membrane bioreactor
MCC	Motor control center
MF	Microfiltration
ML	Megalitre
ML/d	Megalitre per day
MP	Micropollutant
MSDS	Material Safety Data Sheet
MW	Maintenance wash
NF	Nanofiltration

NP	Nanoparticle
NPV	Net Present Value
NQF	National Qualifications Framework
NRF	National Research Foundation
NSAIDs	Non-steroidal anti-inflammatory drugs
O&M	Operations and Maintenance
OSEC	On-site electrolytic chlorination
PAC	Powdered activated carbon
PC	Practical Completion
PFAS	Polyfluorinated substances
PID	Piping and instrumentation diagram
PLC	Programmable logic controller
PPE	Personal protective equipment
PSA	Pressure swing adsorption
PVC	Polyvinyl chloride
QA	Quality assurance
QC	Quality control
QCP	Quality control plan
RGF	Rapid gravity filtration
RO	Reverse osmosis
SABS	South African Bureau of Standards
SALGA	South African Local Government Association
SANS	South African National Standards
SARChI	South African Research Chairs Initiative
SAT	Site Acceptance Testing
SCADA	Supervisory control and data acquisition
SOP	Standard operating procedure
T_e	Removal efficiency
TDS	Total dissolved solids
THM	Trihalomethane
TMP	Transmembrane pressure
TOC	Total organic carbon
TSS	Total suspended solids
UF	Ultrafiltration
UKZN	University of KwaZulu-Natal
UNIZULU	University of Zululand
UoB	University of Birmingham
UP	University of Pretoria
UUW	uMngeni-uThukela Water
UV	Ultraviolet
VSD	Variable speed drive
WHO	World Health Organisation
WISA	Water Institute of Southern Africa

WRAP	Wastewater risk abatement plan
WRC	Water Research Commission
WRSP	Water reuse safety plan
WSP	Water safety plan
WWTW	Wastewater treatment works

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

Historically, about 20% of the earth's land surface experiences drought at any one time. This has increased to 35% by 2020. Over the last 10 years, areas affected by severe droughts have risen from 1% to 3% of the planet's landmass, which is likely to increase (Calow, et al., 2010). Several countries worldwide suffer from water scarcity. In South Africa, drought has resulted in extensive water shortages in several regions. Due to this, local municipalities imposed stringent measures to restrict water usage by their consumers, particularly in the areas that were classified as disaster areas, such as Cape Town and Northern Cape areas.

South Africa is a semi-arid country with limited freshwater resources, and its water supply is further constrained by uneven spatial and temporal distribution of rainfall. The country has a population of over 60 million people, which is projected to reach 80 million by 2050. In addition, rapid urbanization has led to increased demand for water, particularly in the major metropolitan areas such as Johannesburg, Cape Town, and Durban. According to the Department of Water and Sanitation (DWS), South Africa is currently facing a water deficit of 2.7 billion cubic meters per year, which is expected to increase to 3.8 billion cubic meters by 2030 (Kwame, et al., 2022). In an era where conserving water is growing ever more critical, given the shortage of fresh and drinkable water, recycling and reuse plays a pivotal role in driving forward sustainable solutions that will allow for the longevity of South Africa's water supply (Wilkinson, 2017).

South Africa receives an annual rainfall of 464 mm making it a water stressed country, and large portions of the land struggles with water scarcity (Habiyaremye, 2020). This has contributed to the need of water innovation and projects such as water reclamation. Present problems and future challenges are related mainly to limited financial resources and institutional capabilities rather than to resource limitations. Thus, water crises may arise if suitable investments, innovations, and management decisions are not made at the right time. The Department of Water Affairs and Sanitation (DWS) has placed future water resources planning high on its priority list of management functions, with the aim of having sufficient time to prepare for and construct new augmentation schemes and to implement these at the required time without disruptions to major users (Seago, 2016).

The social, economic, and environmental impacts of past water resources development and inevitable prospects of water scarcity are driving the shift to a new water resource management paradigm. New approaches now incorporate the principles of sustainability, environmental ethics, and public participation in project development. With many communities approaching the limits of their available water supplies, water reclamation and reuse have become attractive options for conserving and extending the available water supply. Water reclamation and reuse potentially provide an alternative source of supply to meet both present and future water needs (Asano, et al., 2007); (Swartz, et al., 2015); (Muanda, et al., 2018). In addition, it helps in protecting aquatic ecosystems by decreasing the diversion of freshwater, reducing the quantity of nutrients and other toxic contaminants entering waterways, reducing the need for water control structures such as dams and reservoirs, and complying with environmental regulations by better managing water consumption and wastewater discharges.

Figure 1-1 is a representation of the role of engineered treatment, reclamation, and reuse facilities in the multiple uses of non-conventional water through the hydrological cycle (Aurecon, 2011). Water quality is just as important as quantity if it is to be of any use to the consumer. Figure 1-2 is a representation of the water quality changes during municipal and industrial uses of water in a time sequence (Aurecon, 2011).

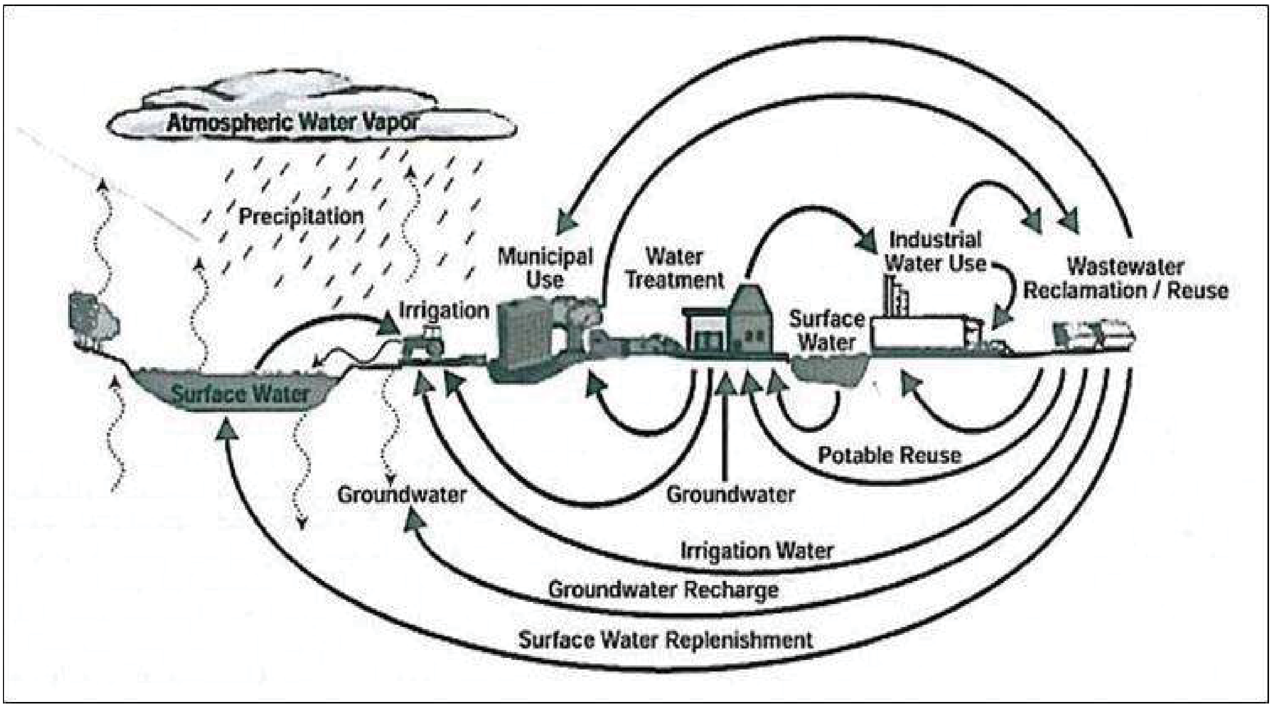

Figure 1-1: The Hydrological Cycle (Aurecon, 2011)

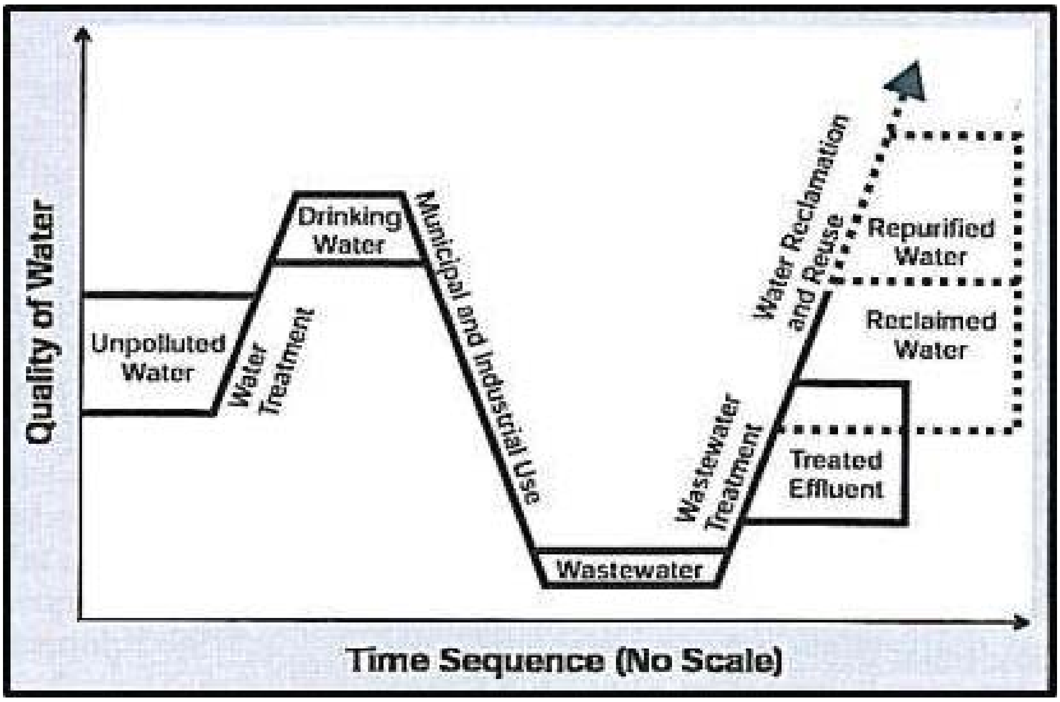

Figure 1-2: Water quality changes in a time sequence (Aurecon, 2011)

As water scarcity becomes a major challenge throughout the planet, the value of this limited commodity is growing exponentially, pushing water treatment, water recycling and water reuse up the priority list in municipalities around the country. By the year 2050, the Earth's population will exceed nine billion (Finley, et al., 2015). Water is being contaminated at a deplorable and unsustainable rate, further exacerbating the need to establish advanced treatment processes and technologies to meet the basic human right of clean drinking water for people.

Some of the advanced treatment processes that can alleviate this strain are seawater desalination, water recycling and reuse of wastewater. Desalination and reuse of wastewater have become attractive options for water augmentation owing to increased efficacy of treatment methods and reduced costs, coupled with the fact that this water source is readily available and near the point of application (Wilkinson, 2017). However, each technology has limitations and must take into account climate change. The goal of this literature review is to examine the current state of direct potable water reuse, including the technology, benefits, challenges, and regulatory frameworks.

The main expectation from this study was for the future implementation of direct reuse as a sustainable potable water source in South Africa, with full public support for the technology, operational, maintenance and monitoring effectiveness, and the final water quality. Other impacts include the development of extensive process expertise in selecting appropriate treatment technologies for the removal of microorganisms and emerging contaminants. It will also guide future research areas to be considered in the field of direct reuse.

1.2 OVERVIEW OF WATER REUSE

Currently, interest in the reuse of wastewater for drinking water requirements is increasing in order to sustain and reduce pressure on natural resources. Rapid population growth, urbanisation, and the unpredictability of conventional water source sustainability (impacted by climate change and source pollution) remain key drivers for water reuse and is spurring large-scale interest in the application of water reclamation and reuse of wastewater to sustain development and economic growth (Wilkinson, 2017). The different types of water reuse are:

1. Direct Potable Water Reuse
2. Indirect Potable Water Reuse
3. Non-Potable Water Reuse

For the purpose of the project, this literature review focuses on direct potable water reuse.

1.3 DIRECT POTABLE WATER REUSE: DEFINITION, IMPORTANCE AND BENEFITS

Direct water reuse is the practice of treating wastewater to a level that meets specific water quality standards and then using it for beneficial purposes without first discharging it to the environment. This type of water reuse includes potable and non-potable applications such as irrigation, industrial processes, and drinking water supply, depending on the level of treatment and the specific quality standards required for the intended use. The importance of direct potable water reuse is increasingly recognised in regions around the world facing water scarcity and water quality challenges. The growing demand for water due to population growth, industrialisation, and climate change is putting pressure on traditional sources of water such as rivers, lakes, and aquifers, which are becoming depleted and contaminated. Direct potable water reuse offers an alternative source of water that can supplement traditional sources and help address water scarcity and quality challenges (Elimelech, 2011).

Furthermore, direct potable water reuse can offer several environmental benefits, including reducing the discharge of wastewater into water bodies, water conservation by reducing the need for fresh water sources, reducing the need for new water supply infrastructure, and improved water security. This is done by providing a reliable source of water that is not dependent on rainfall or surface water availability and lower impact on quality of water bodies through reduced nutrient loading (Ghaffour, et al., 2013); (Hoek, et al., 2019). Direct potable water reuse can also help reduce energy consumption and greenhouse gas emissions by reducing the need for energy-intensive water treatment and transportation systems (Ghaffour, et al., 2013).

1.4 ADVANCED PROCESS TECHNOLOGIES FOR DIRECT POTABLE WATER REUSE

1.4.1 Advanced Oxidation Processes

The removal of recalcitrant trace organic chemicals and certain inorganic pollutants have proven to be a challenge in conventional water and wastewater treatment systems. This has led to the use of advanced oxidation process (AOP) technologies which offer a wider range of reduction and deactivation of contaminating compounds. There are several types of these technologies that have been developed over the years, i.e. peroxone (ozone and hydrogen peroxide) AOP, ultraviolet (UV) irradiation AOP, electrochemical AOP, plasma, electron beam, ultrasound or microwave-based AOPs. This study will focus on the two widely used systems that are ozone-based and UV-based. The working principle of AOPs is based on the in situ generation of strong oxidants for the oxidation of organic and inorganic compounds. This includes processes based on the formation of hydroxyl radicals ($OH^{\cdot}$), sulphate radicals ($SO_4^{\cdot -}$), and chlorine radicals ($Cl^{\cdot}$) (Miklos, et al., 2018). These powerful oxidants destruct the pollutants and transform them into less or non-toxic products (Deng & Zhao, 2015).

The intended AOP configurations for the Darvill FERDP are the peroxone (O_3/H_2O_2) system, O_3/UV irradiation system and/or photolysis of H_2O_2 for production of hydroxyl radicals in different yields. Hydroxyl radicals have a very short lifespan in the region of microseconds and as a result it is produced in situ during application. These radicals are also very powerful oxidants with an oxidation potential of 2.80 V (pH = 0) to 1.95 V (pH = 14) when compared to saturated calomel electrodes (Deng & Zhao, 2015). The basic hydroxyl radical formation from ozone is given by the reaction (1-1) below:

$$3O_3 + H_2O \rightarrow 2OH^{\cdot} + 4O_2 \qquad (1\text{-}1)$$

The generation of hydroxyl radicals can be further improved by dosing other oxidants such as hydrogen peroxide (H_2O_2) or ultraviolet (UV) irradiation. In the peroxone system, hydroperoxide (HO_2^-) is produced from the decomposition of H_2O_2 to further react with ozone and generate more hydroxyl radicals as shown in reactions (1-2) and (1-3) below:

$$H_2O_2 \rightarrow HO_2^- + H^+ \qquad (1\text{-}2)$$
$$HO_2^- + O_3 \rightarrow OH^{\cdot} + O_2^- + O_2 \qquad (1\text{-}3)$$

The increased generation in the irradiation system can be achieved through the photolysis of H_2O_2 as shown in reaction (1-4) below:

$$H_2O_2 \xrightarrow{hv} 2OH^{\cdot} \qquad (1\text{-}4)$$

The AOP systems implemented in this study will be hydrogen peroxide and ozone for the removal of emerging contaminants such as engineered nanomaterials and other organic compounds, i.e. triclosan and triclocarban.

1.4.2 Granular Activated Carbon Filters

Granular activated carbon filters are used in water and wastewater treatment for the removal of dissolved organic matter through adsorption. Organic molecules that possess an affinity for carbon detach from solution and bind with the activated carbon media. Forces of attraction responsible for this bonding are both physical and chemical in nature. Electrostatic forces hold the contaminant when physical binding is predominant. Chemical bonding occurs through surface reactions. Activated carbon is prepared from different materials such as wood, coal, coconut shells, and lignite. The solid material is first carbonated and then activated with hot air or steam. Activated carbon can be applied in two forms in water treatment processes, i.e. powdered activated carbon (PAC) and granular activated carbon (GAC). PAC is dosed into the water that is to be treated and is removed with sludge from the sedimentation units. GAC is used as a filter media through which contaminated water is passed, typically in a counter current flow pattern.

GAC filters will be used in this study to assess the removal of micropollutants at the Darvill FERDP. Feed influent enters the filter from the top at a slow rate to allow sufficient interaction between contaminants and the surface of activated carbon media. The design parameter of importance in the sizing of the column is the ‘empty bed contact time’ which determines the optimum contact time required for a specific contaminant to sufficiently adsorb on the activated carbon media. The contaminants are adsorbed on to the carbon surface and diffuse into the pores through physical and chemical attraction. At saturation, i.e. when the surfaces of the pores are completely covered and contaminant breakthrough occurs, the filter bed requires regeneration to restore its adsorption capacity. A study was conducted on the removal of pharmaceuticals and other micropollutants (MPs) from wastewater using different media filtration (in column tests), including GAC filtration. This study concluded that GAC filtration achieved 97% removal efficiencies (Rostvall, et al., 2018). Further studies at field scale are therefore still required to validate these findings and reduce MPs emissions to the environment.

1.4.3 Ultrafiltration Membrane Treatment

Membrane processes have been employed in the water and wastewater industry in the 19th century as alternatives for conventional systems where smaller sized contaminants cannot be removed. One such membrane that was developed is the ultrafiltration (UF) membrane for the removal of particulates and macromolecules (bacteria in the size range of 10-100 nm). Depending on the emerging contaminants and other organic pollutants present in the treated effluent stream at Darvill WWTW, the membrane will be evaluated for the efficiency in removing those contaminants. The operating principle of UF is through sieving, i.e. separation is by size difference. Pressure is the driving force required to pass water through the membrane. Ultrafiltration is one of the lowest pressure operating membranes requiring up to about 2 bar for the feed stream. These membranes can be manufactured from materials such as cellulose acetate and aromatic polyamide. The feed water has to be carefully treated so that it does not damage the membrane as a result of material of construction compatibility with water chemistry such as pH, presence of chlorides, etc. Membranes are typically configured in modules consisting of the membrane, support structure, feed inlet, concentrate outlet, and permeate outlet. The four main types of modules are hollow fibre, spiral wound, tubular, and capillary modules.

Roccaro (2018) highlighted that no single treatment process can guarantee the required safety of reclaimed water, especially for potable reuse. Figure 1-3 indicates the various possible treatment trains for wastewater reuse. The author stated that a multi-barrier approach, based on a treatment train that includes different processes, should be adopted to control the removal of a wide range of contaminants. It was also noted that multiple processes can remove the same contaminant so that if one fails, or must be taken out of service for maintenance, the system still performs effectively. A combination of treatment technologies can address a broad range of contaminants of emerging concern. Protocols and strategies will be in place to address failures and bring systems back on-line.

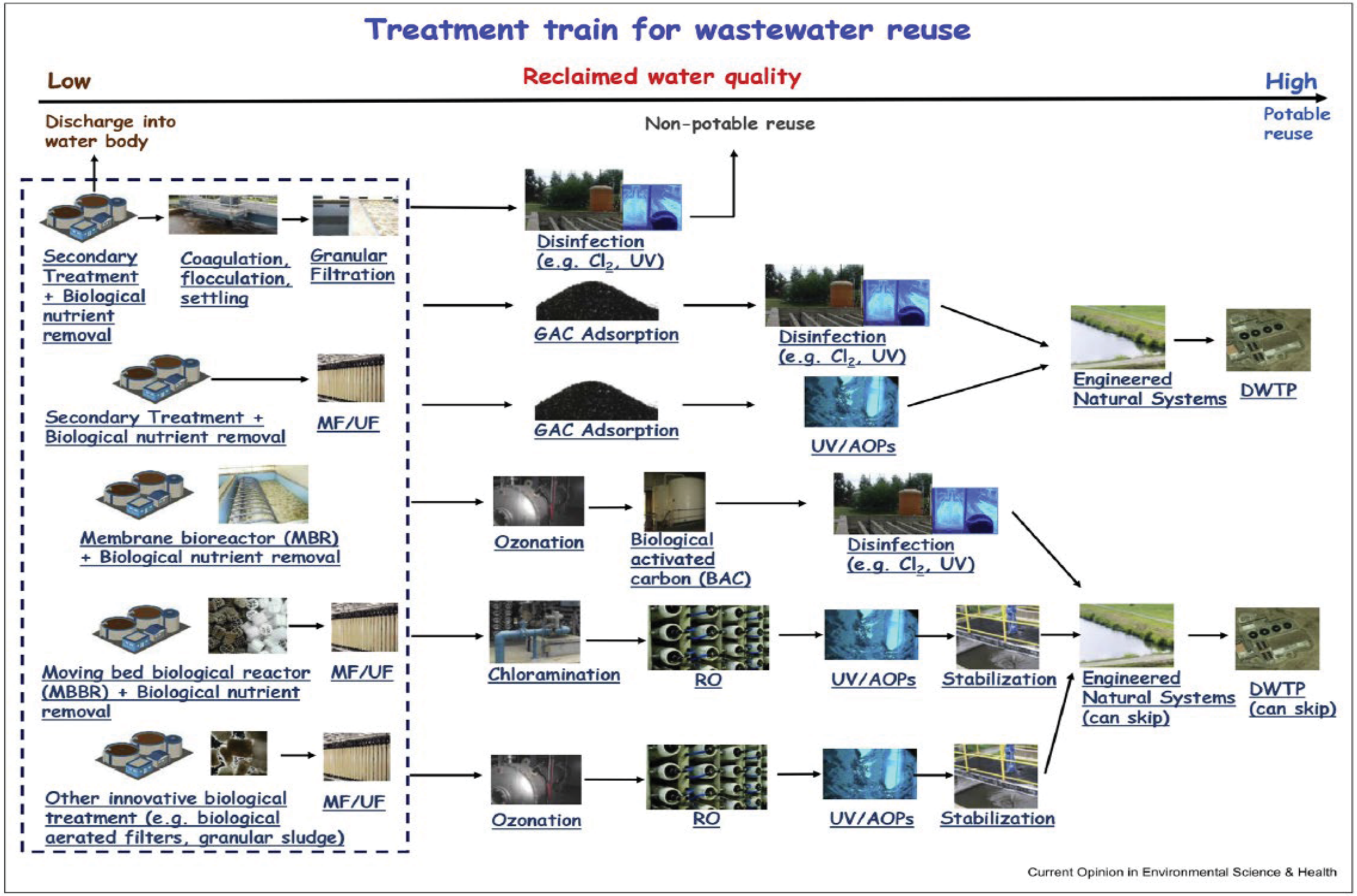

Figure 1-3: Typical treatment trains in wastewater reclamation for alternative reuse options (Roccaro, 2018).

Roccaro (2018) indicated that reverse osmosis (RO) has been proven to be very efficient for potable reuse; however, the employment of the RO process has some drawbacks such as concentrate disposal, corrosion, and the need for stabilization and re-mineralization. The author further noted that schemes without RO may need processes for removal of nitrogen, metals and total dissolved solids (TDS); therefore, if TDS removal is required, RO may be the only choice.

The design of these membranes involves the careful consideration of flux and transmembrane pressure. Flux is a term used to describe the filtration rate in membrane treatment. It is the rate of flow per unit area of membrane, measured in litres per meter squared per hour (LMH). It can be expressed as follows:

$$Flux = \frac{Q}{A} \tag{1-5}$$

Where: 'Q' is the volumetric flowrate across the membrane and 'A' is the cross sectional area of membrane. The transmembrane pressure is calculated as the difference between the module inlet pressure and the pressure at the permeate side. These two parameters are important in the operation and maintenance of the membranes as they give an indication of fouling on the membrane surfaces. Operating the UF at different fluxes can also determine the optimum contaminant rejection and impact on the membrane fouling as a result of different contaminant loadings.

1.4.4 Limitations of Advanced Water Treatment Processes

One of the major limitations of advanced water treatment processes is cost. Advanced water treatment processes are often more expensive than conventional water treatment methods. The cost of advanced water treatment processes is attributed to the high cost of equipment, chemicals, and energy required to operate the systems. Additionally, advanced water treatment processes often require highly skilled personnel to operate and maintain these specialised systems.

Another limitation of advanced water treatment processes is the amount of energy required to operate the systems. Advanced water treatment processes such as reverse osmosis, nanofiltration, and ultrafiltration require a high pressure to push water through the membranes. This high pressure requires a significant amount of energy, which increases the operational cost of the treatment process. Additionally, the use of chemicals in advanced water treatment processes such as oxidation and advanced oxidation processes requires energy to produce the necessary chemical reactions (Petersen & Johnson, 2016). Currently, South Africa is also facing an electricity crisis and equipment such as UF requires a stable supply of electricity. Load shedding occurs often which means interrupted supply of power and the units can fail in these situations when the electricity is unstable, power surges and power dips.

Membrane fouling is a common problem in advanced water treatment processes. Membrane fouling occurs when particles, microorganisms, or other contaminants accumulate on the surface of the membrane, reducing the effectiveness of the treatment process. Membrane fouling can result in reduced water flow, increased energy consumption, and reduced membrane lifespan, which can increase the overall cost of the treatment process. Advanced water treatment processes are effective in removing many contaminants, but they may be limited in their ability to remove certain contaminants such as pesticides, herbicides, and some pharmaceuticals. These contaminants are small and can pass through the membranes used in advanced water treatment processes. Additionally, some contaminants may be resistant to oxidation or advanced oxidation processes, making them difficult to be removed.

The equipment used in advanced water treatment processes require regular maintenance to ensure that the systems are operating effectively. Maintenance requirements may include membrane replacement, cleaning, and chemical replenishment. Regular maintenance can be time-consuming and expensive, which can add to the overall cost of the treatment process.

Advanced water treatment processes can generate waste in the form of concentrated brine or sludge. The disposal of this waste can be challenging and may require additional treatment processes or disposal methods such as landfills. The generation of waste can increase the overall cost of the treatment process and may have environmental impacts. The effectiveness of advanced water treatment processes is dependent on the quality of the source water. Poor quality of the source water can result in reduced effectiveness of the treatment process, increased energy consumption, and increased maintenance requirements. Additionally, certain contaminants may be more difficult to remove from the source water, which can limit the effectiveness of advanced water treatment processes.

Advanced water treatment processes are effective in removing many contaminants from water, but each technology has limitations that must be considered when selecting a treatment process. The cost, energy consumption, membrane fouling, limited removal of some contaminants, maintenance requirements, generation of waste, and dependence on source water quality are all factors that must be considered when selecting a treatment process. Understanding the limitations of advanced water treatment processes can help to ensure that the most effective and efficient treatment process is selected for a particular application.

1.5 LOCAL AND INTERNATIONAL DPR PLANTS/PROJECTS

1.5.1 Overview

Several direct potable reuse plants have been installed worldwide. This section provides an overview of some of the treatment technologies implemented. Most of these processes have been designed with a multi-barrier approach. Tchobanoglous *et al*. (2015) indicated that a multiple-barrier approach to potable reuse needs to include source control (Figure 1-4). Keeping constituents of concern out of the wastewater system through a robust source control program can be the most beneficial, efficient, and cost-effective strategy for managing and treating industrial, commercial, and other contributions to the wastewater supply.

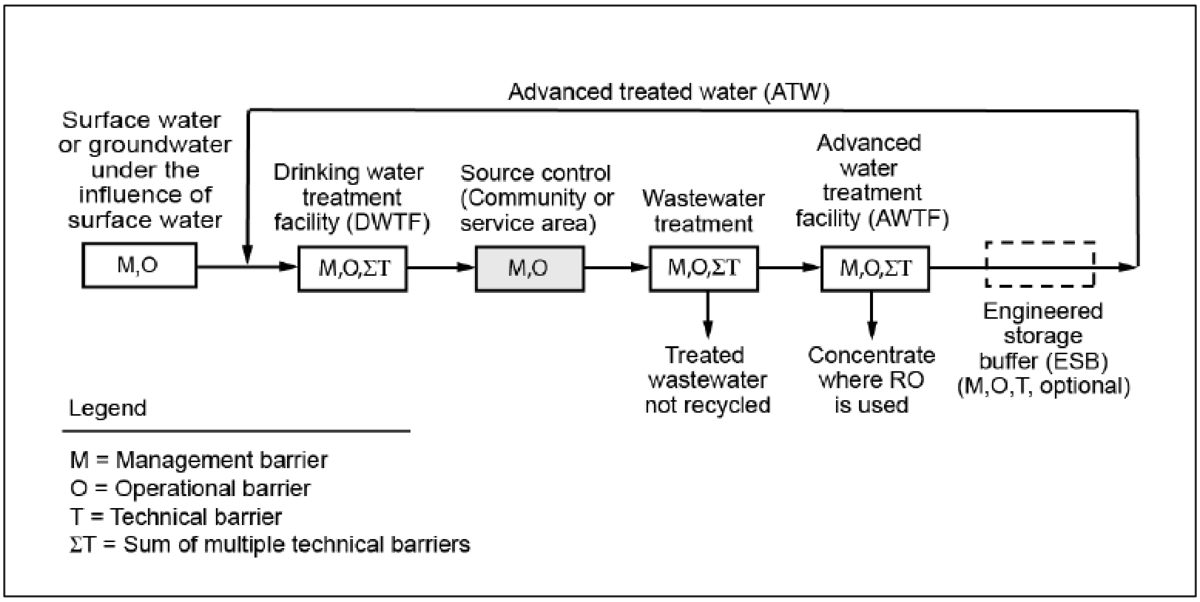

Figure 1-4: Key elements of the technical component of a potable reuse program (Tchobanoglous, et al., 2015).

1.5.2 Namibia

In 1969, the Goreangab Water Treatment Plant, located in Windhoek, Namibia, was modified to treat water from the city's Gammans Wastewater Treatment Plant (du Pisani, 2006). The old Goreangab Water Reclamation Plant (Figure 1-5) had an initial capacity of 4.3 ML/d and was upgraded several times over the years up to an ultimate capacity of 7.5 ML/d in 1997. The city separated industrial effluent from domestic effluent and redirected to a separate plant for treatment.

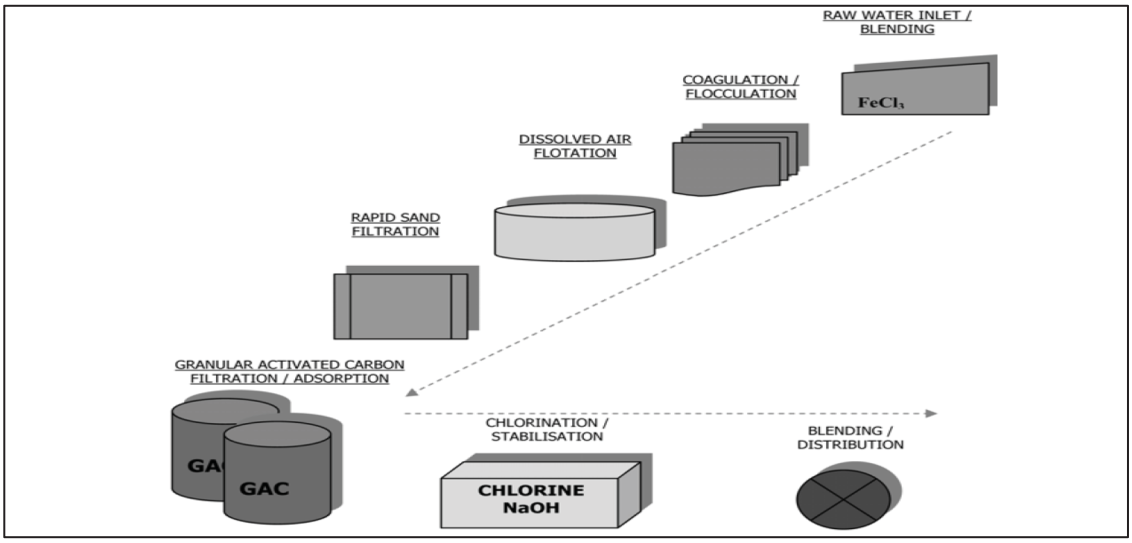

Figure 1-5: Old Goreangab Process Train (du Pisani, 2006)

The new Goreangab Water Reclamation Plant (Figure 1-6) was designed with a multi-barrier design philosophy to a design capacity of 21 ML/d. These barriers include treatment and non-treatment (i.e. operational barriers) processes (du Pisani, 2006). The plant was commissioned in 2002. The process train includes ozonation, chemical dosing, dissolved air flotation, biological and granulated activated carbon filters, ultrafiltration and chlorination.

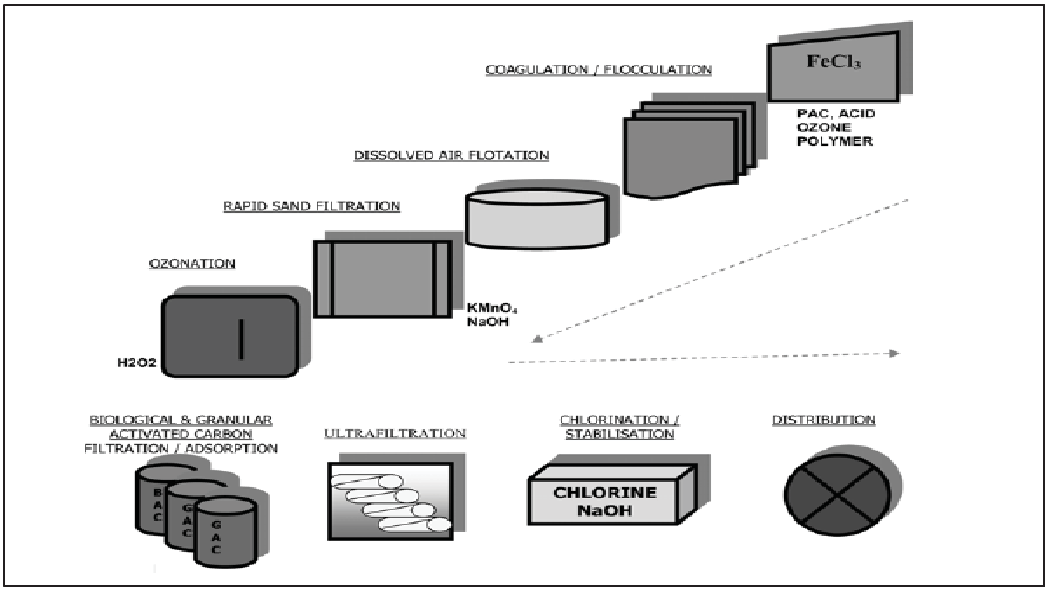

Figure 1-6: New Goreangab Process Train (du Pisani, 2006)

1.5.3 South Africa

Commissioned in 2011, the treatment process at the Beaufort West Water Reclamation Plant (Figure 1-7) uses reverse osmosis as part of a multiple-barrier approach that also incorporates rapid sand filtration, ultrafiltration, advanced oxidation (UV-hydrogen peroxide) and final chlorination.

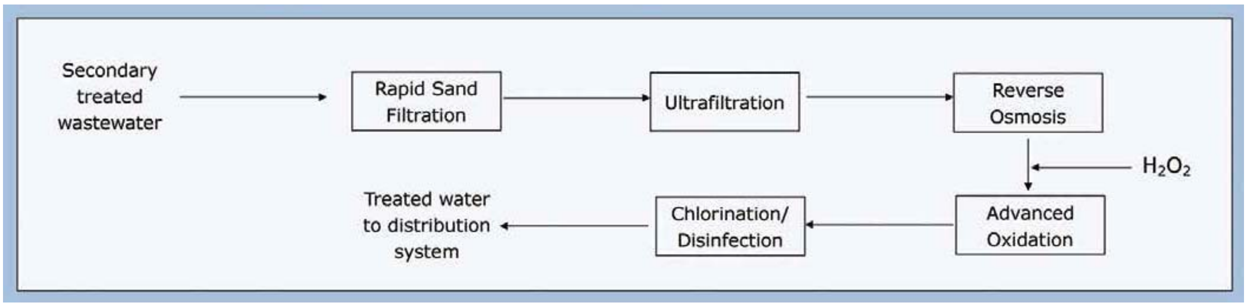

Figure 1-7: Beaufort West Water Reclamation Plant Treatment Processes (Matthews, 2015).

The Western Cape Water Reuse Project involves treating wastewater from the Cape Flats Wastewater Treatment Works and reusing it for irrigation purposes in the Philippi Horticultural Area. The project aims to provide a sustainable source of water for agricultural purposes, particularly in areas where water resources are scarce (Western Cape Government, 2021).

The Durban Water Recycling Plant is located at the eThekwini Water and Sanitation Southern Wastewater Treatment Works and treats domestic and industrial wastewater to near potable water standards. The plant has been successful in reducing the demand for potable water and providing a sustainable source of water for non-potable users in the industrial sector (eThekwini Water Services, 2015).

Mossel Bay Reclamation Plant, located in South Cape District Municipality, Western Cape, treats domestic wastewater to produce high-quality effluent for industrial and commercial reuse. The plant has a capacity of 5.5 ML/d (Swartz, et al., 2022). These are just a few examples of water reuse projects in South Africa. There are other projects that are currently underway or in the planning stages, as the country seeks to find sustainable solutions to its water scarcity challenges.

1.5.4 Others – international plants

When assessing the international treatment train approaches for potable reuse plants (Figure 1-8), it is evident that no standard, correct or best treatment train has been recommended. The treatment trains have been selected for a specific source water and final water specification. The Orange County Water District Groundwater Replenishment System in California relies solely on microfiltration and reverse osmosis to remove suspended solids and organics with ultraviolet light as a final disinfection step. The Singapore NEWater and Orange County Water plants include only membrane processes with UV for disinfection. It should also be noted that the discharge from the Singapore NEWater plant is not introduced into a distribution system, but into a local impoundment which is then abstracted for potable treatment. Many of the California plants also re-inject the output into an aquifer for further aging.

Project	Type of Potable Reuse	Year First Online	Capacity (mgd)	Current Advanced Treatment
Upper Occoquan Service Authority; VA	Surface water augmentation	1978	54	Lime + GMF + GAC + Cl_2
Hueco Bolson Recharge Project, TX	Groundwater recharge by direct injection and spreading basins	1985	10	Lime + GMF + O_3 + GAC + Cl_2
West Basin, CA	Groundwater recharge by direct injection, and various industrial applications	1993	12.5	MF+RO+UV/AOP
Gwinnett County, GA	Surface water augmentation	2000	60	Coag/Sed + UF + O_3 + BAC + O_3
Singapore NEWater	Industrial reuse with a limited amount (5 percent) of surface water augmentation	2000	166[a] (four plants)	MF + RO + UV disinfection
Los Alamitos Seawater Barrier, CA	Groundwater recharge by direct injection	2006	8	MF+RO +UV/AOP
Orange County Water District Groundwater Replenishment System, CA	Groundwater recharge by direct injection and spreading basins	2008	100	MF+RO+UV/AOP

From Schimmoller (2014).

Acronyms: mgd: Million gallons per day. GMF = Granular media filtration. GAC = Granular activated carbon adsorption. Cl_2 = Chlorine disinfection. O_3 = Ozone. MF = Microfiltration. RO = Reverse osmosis. UV/AOP = Ultraviolet with advanced oxidation. Coag/Sed = Coagulation/sedimentation. UF = Ultrafiltration. BAC = Biologically active carbon filtration. UV = Ultraviolet.

[a] As of August 2016.

Figure 1-8: Treatment Technologies Employed at Operational Potable Reuse Plants (Mosher, et al., 2016).

1.6 CHALLENGES AND OPPORTUNITIES OF DIRECT POTABLE REUSE

Direct potable reuse (DPR) presents both challenges and opportunities. While it has the potential to provide a reliable and sustainable source of drinking water, overcoming public perception, developing appropriate regulations, and addressing cost and technical challenges will be important to ensure its successful implementation. The implementation of DPR involves a range of challenges associated with regulatory compliance, which are critical to ensure the safety and reliability of the water supply. These challenges include the development of risk assessments, the establishment of treatment performance goals and the monitoring of water quality and contaminants of emerging concern.

The development of risk assessments is a critical step in the implementation of DPR, as it enables the identification and evaluation of potential risks associated with reusing wastewater for drinking water. Risk assessments involve the identification of potential hazards, the assessment of exposure pathways, and the evaluation of the likelihood and consequences of adverse effects (EPA, 2012). However, the development of risk assessments for DPR is a complex and time-consuming process, which requires significant expertise and resources.

The establishment of treatment performance goals is another critical step in the implementation of DPR. It involves the identification of the required treatment processes, the establishment of treatment performance requirements, and the development of monitoring and reporting procedures (EPA, 2012). The monitoring of water quality is a critical aspect of regulatory compliance for DPR, as it enables the assessment of the effectiveness of the treatment processes and the detection of potential contaminants. Water quality monitoring involves the collection and analysis of samples from the influent and effluent streams, as well as from the distribution system and the end users (EPA, 2012). However, the monitoring of water quality for DPR is a complex and resource-intensive process, which requires a high degree of accuracy and reliability.

Contaminants of emerging concern (CECs) are used to refer to the unregulated organics, trace metals, pathogens, and nanomaterials found in water. CECs are contaminants that have been identified as emerging in the environment, and are not currently regulated by traditional water quality standards. Conventional treatment technologies are not sufficient and unable to completely degrade these compounds. Thus, hundreds of CECs are currently detected in water sources at low concentration (ng/L to µg/L). These emerging contaminants are broadly categorized into two classes based on size namely; micropollutants (micro-sized) and engineered nanomaterials (nano-sized).

Typical CECs include:

- Pharmaceuticals and metabolites – Antibacterials (sulfamethoxazole), analgesics (acetominophen, ibuprofen), beta-blockers (atenolol), antiepileptics (phenytoin, carbamazepine), veterinary and human antibiotics (azithromycin), oral contraceptives (ethinyl estradiol), prescribed and over-the-counter drugs;
- Natural chemicals – e.g. Hormones (17β-estradiol), phytoestrogens, geosmin, 2-methylisoborneol;
- Industrial chemicals – e.g. 1,4-Dioxane, perflurooctanoic acid, methyl tertiary butyl ether, tetrachloroethane;
- Endocrine disrupting compounds – An exogenous compound that mimics or blocks hormonal functions in the body;
- Personal care products – Active ingredients in cosmetics, fragrances, sunscreens, pigments, soap, insect repellents, toothpastes, e.g. antiseptics (triclosan/triclocarban);
- Flame retardants – Active ingredient incorporated into consumer products such as electronics, plastic and children's toys;
- Perfluorinated and brominated compounds – Used as dirt-repellent coatings, spray for leather and textiles;
- Pesticides and herbicides – e.g. Atrazine, lindane, diuron, fipronil; and
- Engineered nanomaterials (ENMs) found in personal care products, pharmaceuticals, pesticides and food products, etc.

Several studies have reported the occurrence of CECs in South African water resources. A study conducted by Chimuka, *et al*. (2015) found that several pharmaceuticals, including carbamazepine and ibuprofen, were present in surface water samples from the Jukskei River in Johannesburg. The study also found that personal care product chemicals, including triclosan and synthetic musks, were present in the same samples. The highest concentrations of total polycyclic aromatic hydrocarbons (PAHs) were found in sediment samples from Johannesburg in the Gauteng province, with concentrations ranging from 1233–136,276 µg/kg for five PAHs. The highest concentration of six PAHs was found in runoff water from the Venda region of the Limpopo province, with a range of 28.7-3192.6 µg/L. Oil spills were also identified as a significant contributor to PAHs in runoff water from the Venda region. Another study that investigated the presence of potential CECs in the drinking water of major cities in South Africa over four seasons revealed that the most frequently detected contaminants were two herbicides, atrazine and terbuthylazine, as well as the anticonvulsant and mood-stabilising drug, carbamazepine. However, the levels of these CECs were found to be well below the maximum levels recommended by the World Health Organization and the US Environmental Protection Agency (Shehu, et al., 2022).

Nanotechnology research and development has grown in South Africa over the last decade, leading to concerns about the potential release of nanoparticles (NPs) into the environment and their effects on public health (Mboyi, et al., 2016); (Gottschalk, et al., 2013). To address these concerns, the Department of Science and Innovation (DSI) established the National Nanotechnology Strategy Group in 2006 (Saidi & Douglas, 2017). The group's primary focus is to establish characterisation centres, research and innovation networks, build human capacity, and establish flagship projects to explore the application of nanotechnology in various fields (Pouris, 2007). Since its establishment, two innovative centres have been established, located at the Council for Scientific and Industrial Research (CSIR) and MINTEK. These centres collaborate with national institutions to conduct research, design, and modelling the application of nanotechnology in water, energy, health, chemical and bio-processing, mining and minerals, advanced materials and manufacturing processes.

The University of Pretoria conducted an online survey in 2016 which indicated that almost 50 consumer products in South Africa contained engineered nanomaterials (ENMs), with zinc oxide (ZnO), carbon nanotubes, titanium dioxide ($nTiO_2$), and silver (Ag) being the most commonly used engineered nanoparticles (ENPs) in electronics, food and beverages, chemical processing, health and fitness, home and garden, appliances, and automotive products (Musee, 2017). There is also a growing concern that the same physicochemical properties that make ENPs useful can also induce toxic effects to the environment and humans. Hence, majority of the research being conducted is focused on risk assessments of ENPs. Several studies have investigated the toxicity of NPs to the ecology, including those conducted by Zhu et al. (2008) on Zebrafish, Federici et al. (2007) on Rainbow trout, Hund-Rincke (2006) on algae, and Lovern (2007) on daphnids.

Preliminary studies have revealed that silver-based nanoparticles are mainly removed through the sludge and partially converted to silver monosulphide (AgS) in wastewater treatment processes (Kaegi, et al., 2011); (Hou, et al., 2012); (Hendren, et al., 2013); (Brunetti, et al., 2015). However, the behaviour of ENPs in wastewater works is highly affected by the presence of electrolytes, organic matter, ionic strength, and pH (Chaúque, et al., 2016). Additionally, copper oxide (CuO), ZnO, and Ag NPs dissociate into Cu^{2+}, Ag^{+}, and Zn^{2+}, increasing their toxicity (Tiede, et al., 2010). Neale et al. (2013) reported that $nSiO_2$ and $nTiO_2$ ENPs could cause a shift in the microbial community after long-term exposure, and Wang et al. (2017) highlighted that the effects of exposure to mixtures of ENPs requires further assessment.

Based on this literature, the experimental methodology for understanding the behaviour and fate of ENPs at Darvill WWTW was developed which aims to modify the biological reactor process on site, i.e. the first barrier for potential reduction of ENPs prior to entering the FERDP. This study will provide valuable information on the fate and behaviour of ENPs and assist in establishing the necessary measures to monitor and control their impact on the environment and public health. Johnson *et al*. (2011) examined the fate of titanium (Ti) NPs of 0.45 µm in an activated sludge plant serving over 200,000 people. These studies revealed a removal of 89%, a decrease from 30 to 3.2 µg/L Ti NPs from influent to effluent and a calculated Ti presence of 305 mg/kg (dry weight basis) in wasted sludge.

Bitragunta *et al*. (2017) studied the detection of TiO_2 in a municipal sewage treatment plant using an inductively coupled plasma mass spectrometry (ICP-MS) and found that the accumulation of Ti was higher in the sludge fraction as compared to the supernatant fraction. This indicated the dominant impact of ENPs to aggregate and settle out from solution. The study also found that TiO_2 underwent hetero-aggregation in the presence of higher molecular weight organic compounds in the wastewater. The overall removal was found to be 79.5% resulting to 0.71 mg/L Ti in the effluent stream going to the environment. Figure 1-9 was extracted from this study and illustrates the typical ENM reduction throughout the conventional wastewater treatment plant at which the reactor removes the most contaminants as biomass.

Chalew, *et al*. (2013) studied the effects of coagulation, flocculation, and sedimentation as well as microfiltration (MF) and ultrafiltration (UF) on removal of ENMs (Ag, TiO_2, and ZnO) from natural waters using coagulant doses ranging from 1 to 10 mg/L of aluminium sulphate. The study found that simulated conventional and advanced (MF and UF) drinking water treatment processes can be effective in removing a large fraction of ENMs; however, they were not found to completely remove ENMs to 3- or 4-log levels similar to those required for bacteria and viruses. Donovan, *et al.* (2016) studied the removal of coated and uncoated ZnO and ceric oxide (CeO_2) NPs during a potable water treatment process involving lime softening, aluminium sulphate coagulation, powdered activated carbon sorption, and disinfection by free chlorine. In all cases, particle concentrations were reduced by a minimum of 60% and most were reduced by > 95% from source water to finished drinking water. The study further concluded that ZnO and CeO_2 can be effectively removed by conventional water treatment processes including lime softening and aluminium sulphate coagulation. All these studies indicate the need to investigate the removal efficiencies of different ENMs as no single process has demonstrated complete removal.

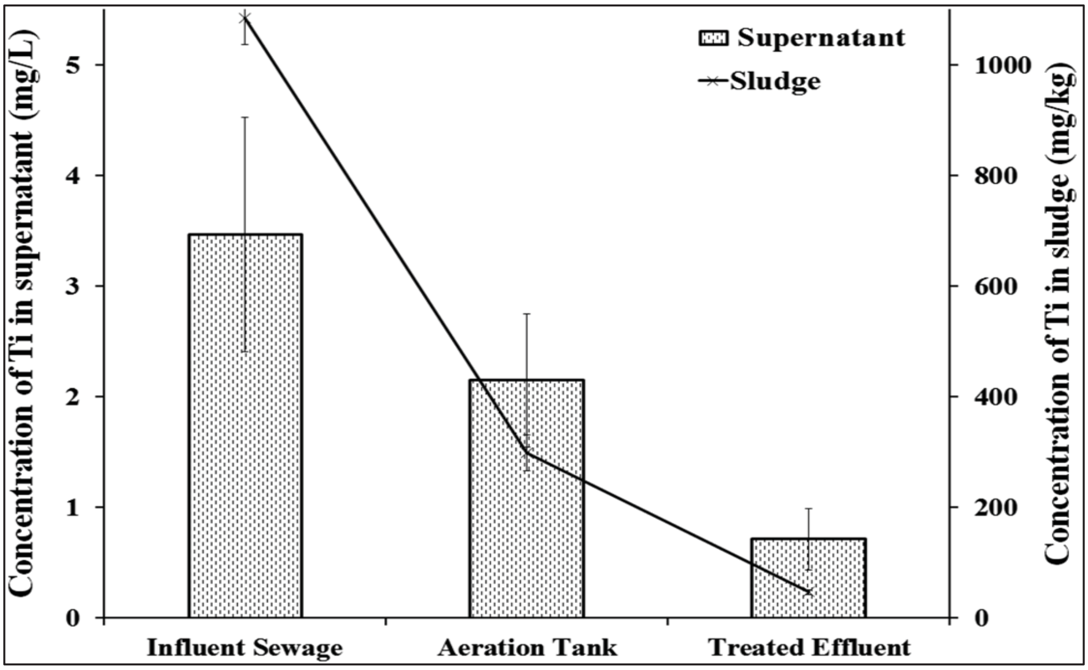

Figure 1-9: Concentration of Ti in supernatant (mg/L) and sludge (mg/kg) fractions of influent sewage, aeration tank contents, and treated effluent of a municipal sewage treatment plant (Bitragunta, et al., 2017).

1.7 REGULATORY FRAMEWORKS

The regulatory frameworks for DPR vary across different regions and countries, reflecting differences in social, economic, and environmental contexts. In the United States, direct water reuse is regulated by the Environmental Protection Agency (EPA) under the Clean Water Act and Safe Drinking Water Act. The EPA has developed guidelines for direct water reuse that establish standards for the treatment of wastewater to ensure that the treated water is safe for its intended use. In Australia, direct water reuse is regulated by the National Health and Medical Research Council (NHMRC). The NHMRC has developed guidelines for direct water reuse that establish standards for the treatment of wastewater to ensure that the treated water is safe for its intended use. In Europe, direct water reuse is regulated by the European Union under the Water Framework Directive. The EU has developed guidelines for direct water reuse that establish standards for the treatment of wastewater to ensure that the treated water is safe for its intended use. Generally, regulatory considerations for DPR are evolving rapidly around the world, reflecting the growing interest in this treatment process and the increasing awareness of the need for sustainable water management. Potential future developments in this field include the integration of emerging technologies, the development of new guidelines and regulations, and the establishment of international standards.

The monitoring of water quality is a critical aspect of regulatory compliance for DPR, as it enables the assessment of the effectiveness of the treatment processes and the detection of potential contaminants. Water quality monitoring involves the collection and analysis of samples from the influent and effluent streams, as well as from the distribution system and the end users (EPA, 2012). However, the monitoring of water quality for DPR is a complex and resource-intensive process, which requires a high degree of accuracy and reliability.

The following water quality standards and guidelines have been developed in South Africa for monitoring minimum standards for potable water use and discharges into water resources from wastewater treatment processes and industries (NWRS II, 2013):

- South African National Standard (SANS) 241: 2015 for drinking water;
- South African Water Quality Guidelines for a number of different water user sectors (DWAF, 1996); and
- General and Special Standards pertaining to the discharge of treated wastewater to the water resource.

New regulatory and guiding documents will need to be developed by the Department of Water and Sanitation for water reuse. This may include aspects on water quality variables of concern, quantification of risks and acceptable risk levels and monitoring requirements in terms of frequency and location of sampling points, etc. (NWRS II, 2013). "A Water Reclamation and Reuse Guide for South African Municipal Engineers" has been developed by Swartz et al. (2022) with the support of Water Research Commission which aims to provide guidelines for the municipal engineers when implementing reclamation and reuse projects. The guideline may be used as a basis to develop a national water reuse guideline for South Africa.

1.8 SUSTAINABILITY OF A DPR PLANT

In order to achieve long term sustainability, the objectives of urban water systems need to go beyond the protection of public health and receiving water bodies and also focus on strategies to reduce the impacts on natural resources, to optimise the use of energy and water and to reduce waste generation. These urban systems should adopt innovative approaches to wastewater management to maximise the recovery of useful materials and energy, thereby reducing emission releases (Buonocore, et al., 2016).

When assessing the economic viability of a water supply project, it is important to understand the difference between economic costs and benefits and financial accounting costs and benefits (National Research Council, 2008). Financial costs involve how much a water utility has to pay to construct and operate the project, including interest costs. Economic costs account for all of the costs to whichever party they may accrue. The concept of economic cost has been linked to the idea of a "triple bottom line" approach. The project sponsor is considered to have an obligation to examine the environmental and social impacts, not just the profitability. One challenge associated with the "triple bottom line" approach is the economic valuation, i.e. the difficulty of evaluating environmental and social impacts (Norman & MacDonald, 2004).This challenge invariably means that the approach will offer more guidance than quantitative comparative analysis, although the concept does alert business and public agency leaders that the public is aware of the difficulty in monetizing impacts of their practices and the importance of striving for full accountability for ones impact on society and the environment. In general, the sustainability of a DPR plant can be evaluated based on several environmental, economic, social factors, health and safety. Life cycle cost analysis (LCCA), life cycle assessment (LCA), public acceptance protocol and operational monitoring protocol are the most appropriate tools available to evaluate the sustainability of DPR.

1.8.1 Life Cycle Costing Analysis

A life cycle costing analysis (LCCA) for a DPR plant involves assessing all costs associated with the planning, design, construction, operation, maintenance, and decommissioning of the facility over its lifespan. The purpose of life cycle costing is to support decisions on the acquisition, exploitation, rehabilitation and disposal of assets. Some common objectives of life cycle costing are (van den Boomen, et al., 2017):

- Identification of major cost drivers;
- Evaluation of the economic viability of investments;
- Comparison of alternative assets; and

- Long-term financial planning.

Water utilities and Municipalities must ensure that the monetary value invested in projects would be most economically advantageous over a long period. Utilities are no longer interested in a cheaper solution because often the minimisation of production costs does not promote optimal performance throughout the life cycle (Oberg, 2005). This highlights the importance of a life cycle costing analysis (LCCA) applied to the design, construction, operation, maintenance and decommissioning of a direct potable reuse (DPR) facility. To achieve efficient functional performance and enhance the quality of economic efficiency, life cycle costs must be evaluated as part of the decision-making process.

The methodology for conducting the LCCA can be based on the following steps (Langdon, 2007):

1. Purpose
2. Preliminary identification of parameters and analysis requirements – confirmation of project and facility requirements
3. Assembly of cost and performance data
4. Finalise parameters for analysis
5. LCCA and results
6. Interpretation of results
7. Reporting

The formulas that are used to conduct a LCCA are:

$$Total\ Costs = \sum Annual\ Costs + \sum Amortized\ Capital\ Costs \quad (1\text{-}6)$$

$$Total\ Capital\ Costs = Purchased\ equipment\ Costs + Direct\ Costs + Indirect\ Costs \quad (1\text{-}7)$$

$$Total\ Annual\ Costs = OC + RC + MC + CC + EC \quad (1\text{-}8)$$

$$NPV = \sum \frac{Cash\ Flow_i}{(1+i)^n} \quad (1\text{-}9)$$

Where: OC=Operational costs, MC= Material costs, RC=Replacement (i.e. Maintenance) costs, CC= Chemical costs, EC=Energy costs, NPV= Net Present Value, i = Discount rate, and n = Time period.

Accurate capital and operational expenditure estimates and detailed life cycle costing are required and should include adequate risk factors that allow for unexpected changes in demand, escalation and changes in rates and availability of consumables such as electricity and treatment chemicals (Turner, et al., 2015).

There are various studies conducted previously on the life cycle costs related to construction, operation and maintenance of water reuse plants in South Africa. In 2015, the Water Research Commission published a report series titled “Investigation into the Cost and Operation of Southern African Desalination and Water Reuse Plants”. The comprehensive study was conducted by Royal HaskoningDHV and detailed the cost, operational and maintenance (O&M) aspects of direct potable reuse plants. Table 1-1 below is an extract of the results the study conducted on the various water reuse plants.

Table 1-1: Summary of results for O&M costs for water reuse plants (Turner, et al., 2015)

	Water Reuse Plants			
Plant	Beaufort West reclamation plant	Windhoek Goreangab reclamation plant	George UF plant	Mossel Bay UF/RO plant
Size of Plant	2.1 Mℓ/d	21 Mℓ/d	8.5 Mℓ	5 Mℓ/d
Type of Plant	Reuse: Direct potable	Reuse: Direct potable	Reuse: Indirect potable	Reuse: Direct industrial
Owner	Beaufort West Municipality	Windhoek Municipality	George Municipality	Mossel Bay Municipality
Operator	Water & Wastewater Eng.	Wingoc	George Municipality	VWS (Veolia)
Operational Status	1.2 Mℓ/day	17.5 Mℓ/day	Zero production	Zero production
Completed	2010	2001	2010	2010
Capital Cost - at time of construction - Adjusted for 2014/15 - Per unit capacity	 R26.5 mill R34 mill R16.22 mill/Mℓ/day	 R122 mill R260 mill R12.38 mill/Mℓ/day	 R36 mill (plant) R46 mill R5.14 mill/Mℓ/day	 R40 mill R51 mill R10.19 mill/Mℓ/day
O&M Cost (2014/15)	R6.92/m³	R4.87/m³	R2.11/m³	R2.72/m³
Energy Use	2.07 kWh/m³	0.57 kWh/m³	0.23 kWh/m³	0.73 kWh/m³
Electricity Cost	R1.88/m³	R0.57/m³	R0.23/m³	R0.64/m³
Chemicals	R0.85/m³	R1.55/m³	R0.44/m³	R0.18/m³
Consumables	R0.50/m³	R1.00/m³	R0.50/m³	R0.50/m³
Maintenance	R1.01/m³	R0.78/m³	R0.23/m³	R0.49/m³
Staff	R1.96/m³	R0.88/m³	R0.49/m³	R0.79/m³
Laboratory cost	R0.47/m³	R0.06/m³	R0.15/m³	R0.07/m³
SHEQ	R0.23/m³	R0.03/m³	R0.08/m³	R0.05/m³

The results obtained from the study conducted by Turner, et al. (2015) can be utilized for the purpose of cost comparison concerning the preliminary LCCA results obtained for the Darvill FERDP. The study provides an indication of how well the results will compare to actual data obtained from water reuse plants that have been in operation for over a decade. Of particular interest for comparison is the data presented for Beaufort West Reclamation Plant's, as this plant is of similar capacity to Darvill FERDP, although, with the inclusion of the reverse osmosis treatment process. The ultimate goal of the LCCA for the Darvill Final Effluent Reuse Demonstration Plant (FERDP) is to provide uMngeni-uThukela Water with a holistic view of the costs associated with a DPR plant over its life span, enabling the water utility to make informed decisions regarding its feasibility and long-term viability. This information will be essential to the South African water sector for planning and budgeting for DPR projects and ensuring efficient and sustainable water reuse solutions.

1.8.2 Public Acceptance

Direct potable reuse involves the reclamation of wastewater, using advanced treatment processes, to produce water that is safe for human consumption and use. Public perception of wastewater recycling for direct potable reuse is highly variable due to the perceived health risk associated with DPR. Rocarro (2018) highlighted the impact of water quality issues relating to the role of water treatment plants and how this impacts on DPR (refer to Figure 1-10).

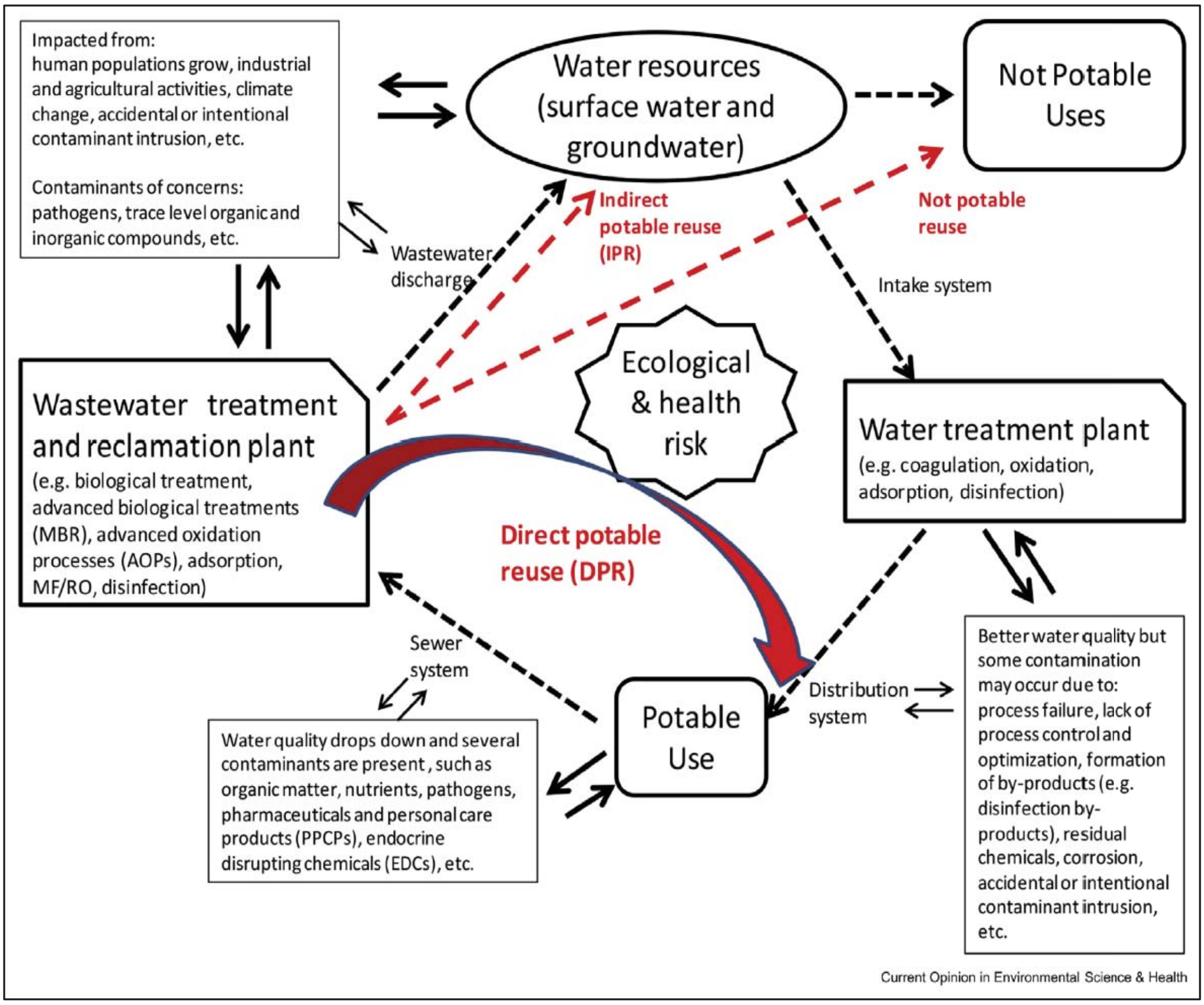

Figure 1-10: Quality issues in the water cycle and role of water treatment plants, with emphasis on direct potable reuse (Roccaro, 2018)

Adewumi *et al*. (2010) conducted a study in partnership with the Water Research Commission (Project No. K5/1701) and some of the recommendations to facilitate the broader implementation of wastewater reuse are summarised below:

- There is urgent need for the DWS to develop a national guideline document that presents a consistent technical guide for the implementation of wastewater reuse and reuse systems;
- A life cycle cost-benefit analysis needs to be carried out within the context of other water resource alternatives and a full appreciation of the true costs of drinking water supply provision to ensure economic viability;
- Incentives to achieve wastewater tariffs lower than drinking water tariffs must be considered. This may include subsidies to consumers for wastewater reuse, utilisation of existing infrastructure (e.g. WWTWs), and/or the installation of a reuse system during the construction of new buildings;
- To guarantee a high level of service for wastewater reuse, a programme of regular control and monitoring of influent from various sources (especially industries) should be implemented by local authorities. In addition, many local authorities need to be equipped with qualified personnel that will undertake control and monitoring tasks and enforce by-laws;
- Willingness to adopt wastewater reuse by potential users is critical prior to implementation. Decision-makers must also understand the conditions under which potential users will be willing to reuse wastewater;
- If wide-area urban systems are to be implemented, local authorities must first consistently perform well in the services rendered to communities. This will increase consumers' trust in

the local authority's ability to implement reuse systems and therefore reduce any potential risks to public health and safety. It is fruitless for local authorities to consider implementing wastewater reuse when existing service levels are low; and

- The general awareness of decision-makers, builders, plumbers, product manufacturers, architects, etc. to the potential of wastewater reuse will be beneficial for a better understanding and broader implementation of wastewater reuse. An integrated water reuse education/awareness programme would be beneficial for potential consumers to understand wastewater reuse. This programme can be enhanced using case studies of wastewater reuse in other communities.

DWS published the 'National Water Resources Strategy 2 (NWRSII): National Strategy for Water Reuse' in 2013 which has encompassed the above recommendations in a more holistic approach to water management. A short term WRC project (KV320/13) was conducted by van Niekerk and Schneider (2013) to generate a sector discussion document for the implementation of the water re-use strategy. The authors noted that public perceptions and community acceptance of direct reuse of treated wastewater remains a challenge to direct reuse. Sgroi *et al*. (2018) also stated that a holistic approach that takes into account all the reuse factors (political, decisional, social, economic, technological and environmental factors) is needed for a sustainable water reuse implementation.

Marks (2006) conducted research on the social effects of implementing innovative solutions to sustainable water management in United States and Australia. The study considered recent potable reuse proposals and illustrated that public involvement is both an expectation and requirement for the introduction of innovative solutions to water management. The research showed that there needs to be greater dialogue throughout whole communities, including government, politicians, water professionals, media, business, interest groups, and the general public. The author noted that informed deliberations should include complete information on the status quo (including instances of 'unplanned' and existing potable reuse) and the full range of alternatives available, which may include further conservation efforts. Mark (2006) stated that the aim of these negotiations should be to arrive at a sustainable outcome, not the acceptance of a system preferred by its proponents.

Binz *et al*., (2016) focused on the implementation of reuse schemes in California and the research showed that 'acceptance' of reuse technology must be understood as a "complex socio-technical development process" and that recent successes in California are the result of a "40-year-long system building process" to legitimise potable reuse. Examples of some of the forms of institutional work that is required is shown in Figure 1-11. Smith *et al*., 2017 indicated that such efforts will allow the field to move past the view that deeply entrenched emotional reactions are fixed, and improve understandings of how they can potentially be shifted through long-term societal legitimation and narrative building processes.

Form of institutional work	Examples related to water reuse
Changing normative associations	Associating water reuse with its positive applications (e.g. groundwater augmentation) instead of its source (waste/sewage disposal)
Constructing normative networks	Creating independent review panels for reuse schemes; certification processes for treatment technologies or water quality
Mimicry	Selling bottled recycled water alongside bottled spring water
Educating	Providing information about treatment processes; publishing results from water testing; conducting tours of treatment plants
Valorising and demonising	Giving awards to reuse schemes, or the people/organisations associated with them; using celebrities to promote recycled water
Mythologizing	Outlining the history of a well known 'great' reuse scheme
Imagery	Images of children drinking or playing in clean water; using evocative positive terminology such as 'water recycling'

Figure 1-11: Selected examples of forms of institutional work, related to public engagement around water reuse (adapted from Binz *et al.*, 2016 and cited by Smith *et al.*, 2017)

Smith *et al*. (2017) conducted a review of public responses to direct reuse in California. The authors' analyses illustrated the kinds of strategies that opponents of reuse schemes have successfully employed to undermine legitimation. The study highlighted an example of the chief opposition group in the Toowoomba case were the group was able to undertake a highly emotive and aggressive campaign, which was even reflected in the name of their group 'Citizens Against Drinking Sewage'. The authors stated that the group effectively employed negative imagery in order to appeal directly to residents' affective reactions by emphasising potential health risks as well as concerns over the town's image of a 'Garden City' being replaced by 'Poowoomba', making it less attractive to investment. The study also noted that recent developments in potable reuse schemes (indirect and direct) and the support that these have generated (e.g. in San Diego) have shown that this may no longer be such a significant factor. However, Smith *et al*. (2017) also indicated that 'awareness of water supply problems' and the 'promotion of water conservation' do not necessarily improve acceptance of reuse and treating water reuse as a mechanism to address a water supply deficit can backfire.

The review conducted by Smith *et al*. (2017) also showed that some significant advancements in thinking in this field stem from the increasingly sophisticated understanding of the 'yuck factor' and the role of such pre-cognitive affective reactions in shaping responses. The authors noted that recent research has shown that awareness of existing unplanned (de facto) reuse practices has the potential to improve acceptance and that studies should focus on real-world schemes that have generated positive reactions, not just those that have faced opposition. Overall, the study revealed that much of the work in this area has benefited from strong engagement with other related literature (risk perception, behavioural psychology, socio-technical theory, etc.) and future research should continue to promote cross-fertilisation, especially on the aspect of understanding affective reactions. These preliminary literature studies will assist towards the development of a methodology for addressing public perceptions and acceptance of the direct reuse at the Darvill FERDP. It is envisaged that the annual national forum sessions will be utilized for engaging with all stakeholders and slowly sensitising individuals on the issues and strategies that are in-place by uMngeni-uThukela Water and the research team.

1.8.3 Operational Monitoring (Process Control)

Operational monitoring is aimed at understanding the treatment performance of the plant. It is conducted to ensure that the plant is operating at its optimal levels and producing the water quality required. There are specific targets that must be met and when there is non-compliance, it should trigger a corrective action plan to protect the water quality and eliminate risk to the public. Operational monitoring monitors less parameters but at higher frequencies. Some of the main parameters that are monitored are temperature, pressure, differential pressure, and flow rate; and quality parameters like pH, turbidity, electric conductivity and UV_{254} (surrogate measurement for organic matter content) (Swartz, et al., 2022). Table 1-2 shows the operating parameters for measuring unit performance. Each treatment unit should also be monitored to assess the unit's performance and efficiency.

Table 1-2: Operating parameters for measuring unit performance (Swartz, et al., 2016)

Parameter	Measurement Method	Minimum Frequency
pH	On-line, portable instrument	Hourly
Total suspended solids	Laboratory/ On-line (secondary)	Four times per day
Electrical conductivity	On-line, portable instrument	Hourly
Colour	Laboratory/ On-line (secondary)	Hourly
Turbidity	On-line, portable instrument	Hourly
Dissolved organic carbon	Laboratory/ On-line (secondary)	Hourly
Inorganics	Laboratory	Daily
Organics	Laboratory/ On-line (secondary)	Four times per day
Microbiological	Laboratory	Daily
UV_{254}	On-line	Hourly

Feedback from these measurements should necessitate the troubleshooting or optimisation that is required. Figure 1-12 shows the advanced treatment processes, contaminants removal, residuals, by-products, applicability and costs and this can assist to determine what should be measured in process units (Roccaro, 2018).

Process	Nutrients removal	TSS removal	TDS removal	Pathogens removal	Metals removal	CEC removal	Residuals and/or By-products	Operator skill based on current application	Relative complexity of technology	Maturity level of technology	Cost (capital + O&M)
Biological N and P removal	High (N, P)	Medium	No/Negligible	Low	No/Negligible	No/Negligible	Sludge	Low	Low	High	Medium
P precipitation	High (P)	Medium/High	No/Negligible	Low	High	No/Negligible	Sludge	Low	Low	High	Medium
MBR	Low/High	High	No/Negligible	Medium	No/Negligible	Low	Sludge	Low	Low/Medium	Medium/High	Medium/High
Granular media filtration	Low	High	No/Negligible	Low/Medium	No/Negligible	No/Negligible	Backwashing water	Low	Low	High	Low
Coagulation	Low	High	No/Negligible	Low/Medium	High	No/Negligible	Backwashing water and sludge	Low	Low	High	Low
GAC/PAC adsorption	Low	Low/Medium	No/Negligible	Low	Low/Medium	Low/High	Exhausted GAC/PAC	Low	Low	High	Medium
O_3/BAC	Low/Medium	Medium	No/Negligible	Low/Medium	No/Negligible	Low/High	Limited by-products thanks to BAC	Low/Medium	Medium	Low/Medium	Medium/High
MF/UF	Low	High	No/Negligible	Medium	No/Negligible	No/Negligible	Backwashing water	Low	Low	High	Low
NF/RO	High (N, P)	Low	High	High/Medium	High	High	Concentrate	Low/Medium	Medium	High	High
Chlorination	Low	No/Negligible	No/Negligible	High/Medium	No/Negligible	Low/Medium	By-products (e.g. THM, HAA)	Low	Low	High	Low
Chloramination	No/Negligible	No/Negligible	No/Negligible	Low/Medium	No/Negligible	Low	By-products (e.g. HAA, NDMA)	Low/Medium	Low	High	Low
UV disinfection	No/Negligible	No/Negligible	No/Negligible	High	No/Negligible	Low	No/Negligible	Low/Medium	Low	High	Low/ Medium
Ozonation	Low	Low/Medium	No/Negligible	High/Medium	No/Negligible	High	By-products (e.g. bromate, NDMA)	Medium	Medium	High	Medium
UV/H_2O_2	No/Negligible	No/Negligible	No/Negligible	High	No/Negligible	High	By-products (e.g. CEC transformation products)	Low/Medium	Medium	High	Medium
Other AOPs (e.g. photocatalysis)	No/Negligible	No/Negligible	No/Negligible	High/Medium	No/Negligible	High	By-products (e.g. CEC transformation products)	Low/High	High	Low/Medium	Medium/High
SAT	Low	Medium	Low	Low/Medium	Low/Medium	Low/Medium	No/Negligible	Low	Low	Medium	Low
Riverbank filtration	Low	Medium/High	Low	Low/Medium	Low/Medium	Low/Medium	No/Negligible	Low	Low	Medium	Low
Constructed wetlands	Low	Medium	No/Negligible	Low/Medium	Low/Medium	Low/Medium	Biomass	Low	Low	Medium	Low

Figure 1-12: Advanced treatment processes, contaminants removal, residuals, by-products, applicability and costs (Roccaro, 2018).

The removal efficiency (T_e) of major pollutants played an integral part of the performance evaluation of the treatment process. Removal efficiency can be calculated for each water quality parameter using either equation (1-10) or (1-11) below.

$$T_e = \frac{Influent\ concentration - Effluent\ concentration}{Influent\ concentration}\ x\ 100 \qquad (1\text{-}10)$$

$$Log_{10}\ removal = log_{10}(C_i/C_o) \qquad (1\text{-}11)$$

Where: C_i is the initial concentration and C_o is the final concentration

Log removal is used to determine the process effectiveness of pathogen and emerging contaminant removal for various advanced technologies. The log removal for some indicators and pathogenic microorganisms is presented in Table 1-3 below. The removal efficiencies of some common CECs are shown in Figure 1-13 below.

Table 1-3: Typical log removals achieved by various processes (EPA, 2012 cited by Bigen Africa Report, 2013)

Type of Microorganism	Indicator microorganisms			Pathogenic microorganism				
	Escherichia coli (indicator bacteria)	Clostridium perfringens	Phage (indicator virus)	Enteric bacteria (e.g., *Campylobacter*)	Enteric viruses	Giardia lamblia	Cryptosporidium parvum	Helminths
Bacteria	X	X		X				
Protozoa and helminths						X	X	X
Viruses			X		X			
Indicative Log Reductions in Various Stage of Wastewater Treatment								
Secondary treatment	1-3	0.5-1	0.5-2.5	1-3	0.5-2	0.5-1.5	0.5-1	0-2
Dual media filtration	0-1	0-1	1-4	0-1	0.5-3	1-3	1.5-2.5	2-3
Membrane filtration (UF, NF, and RO)	4->6	>6	2->6	>6	2->6	>6	4->6	>6
Reservoir storage	1-5	N/A	1-4	1-5	1-4	3-4	1-3.5	1.5->3
Ozonation	2-6	0-0.5	2-6	2-6	3-6	2-4	1-2	N/A
UV disinfection	2->6	N/A	3->6	2->6	1->6	3->6	3->6	N/A
Advanced oxidation	>6	N/A	>6	>6	>6	>6	>6	N/A
Chlorination	2->6	1-2	0-2.5	2->6	1-3	0.5-1.5	0-0.5	0-1

PPCP Classification	Cl_2	UV	O_3/AOP	GAC	NF	RO
Antibiotics	P-G	F-G	L-E	F-G	E	E
Antidepressants	P-F	F-G	L-E	G-E	G-E	E
Anti-inflammatory	P-F	E	E	E	G-E	E
Lipid regulators	P-F	F-G	E	E	G-E	E
X-ray contrast media	P-F	F-G	L-E	G-E	G-E	E
Psychiatric control	P-F	F-G	L-E	G-E	G-E	E
Synthetic musk	P-F	E	L-E	G-E	G-E	E
Sunscreens	P-F	F-G	L-E	G-E	G-E	E
Antimicrobials	P-F	F-G	L-E	G-E	G-E	E
Surfactants/detergents	P	F-G	F-G	E	E	E

From Snyder et al. (2003).

Cl_2 = Chlorination. O_3/AOP = Ozonation or other advanced oxidation process. GAC = Granular activated carbon.

NF = Nanofiltration. PPCP = Pharmaceuticals and personal care products. RO = Reverse osmosis.

E = Excellent (>90 percent). G = Good (70-90 percent). F = Fair (40-70 percent). L =Low (20-40 percent). P = Poor (<20 percent).

Figure 1-13: Removal Efficiency of Engineered Systems for Pharmaceuticals and Personal Care Products (Mosher, et al., 2016)

1.8.5 Hazard analysis and critical control points

Halliwell *et al.* (2014) developed a hazard analysis and critical control point approach (HACCP) to detect and correct deviations in quality processes at the earliest possible opportunity (Figure 1-15). Halliwell *et al*. (2014) developed a five-question metric for identifying critical control points (CCP) in reuse systems. Walker *et al.* (2016) modified one of the questions to be specific to a potable reuse scenario, in which the potential hazards are specifically phrased in terms of pathogen log reduction and water quality targets. The HACCP framework for pathogens and CECs will be utilised to investigate whether the current technologies are able to effectively remove bacteria, viruses, protozoa and emerging contaminants and to make recommendations for implementation on a large scale plant.

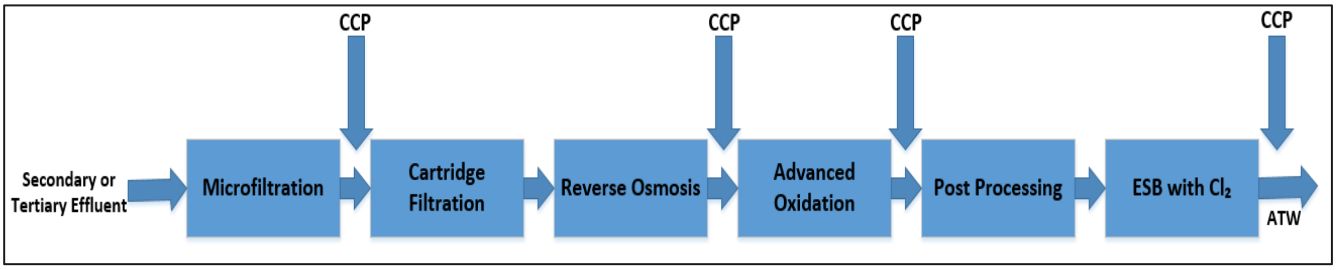

Figure 1-15: hazard analysis and critical control point approach (HACCP) Halliwell *et al.* (2014).

1.9 FUTURE OF DIRECT POTABLE REUSE

The future of direct potable reuse (DPR) is promising due to increasing water scarcity and the need for sustainable water management practices. Recent developments in technology and treatment processes have significantly improved the efficiency and cost-effectiveness of direct water reuse. Membrane technologies such as reverse osmosis and ultrafiltration have become more widely used and accepted, and advanced oxidation processes have shown promising results in removing CECs and trace organic compounds. In addition, new approaches, such as the use of ceramic membranes and forward osmosis, are being investigated for their potential to enhance the efficiency and sustainability of direct water reuse systems.

Cui et al. (2018) reported that DPR is expected to become an increasingly attractive option for addressing water scarcity in arid and semi-arid regions, particularly in areas with limited surface water or groundwater resources, however, significant technical, social, and regulatory challenges remain to be addressed in order to expand the practice. In a review by Ruffell et al. (2021), it was suggested that the future of DPR lies in increasing public awareness, understanding, and acceptance of the practice. The review emphasises the importance of building public trust through transparent and effective communication, engaging stakeholders in the decision-making process, and ensuring that DPR is safe, reliable, and cost-effective.

In terms of regulation and policy, many countries and regions are beginning to recognise the potential benefits of direct water reuse and are taking steps to facilitate its implementation. In Australia, the National Water Commission has developed guidelines for the management of water recycling schemes and has established a framework for the assessment and approval of direct potable reuse projects. In South Africa, direct water reuse is gaining traction as a viable option for water supply augmentation, leading to the development of a water reuse guideline for municipal engineers in 2022.

According to a study by Schäfer et al. (2019), DPR has the potential to be an important part of the water supply mix in many regions, especially in areas facing water scarcity. The study analysed the feasibility and sustainability of DPR in various regions across the globe and found that DPR could be a cost-effective and sustainable water resource management strategy in many locations. Another study by Knappe et al. (2019) investigated the benefits, challenges, and opportunities associated with DPR, and concluded that DPR could play a significant role in meeting future water demands in the region. Overall, these studies suggest that DPR has great potential as a sustainable and cost-effective approach to addressing water scarcity and meeting future water demands. However, all these studies also highlight the need for continued research and development to optimise DPR technologies and ensure their long-term sustainability.

Overall, the future of direct potable reuse looks promising as technology advances, public acceptance improves and regulatory frameworks evolve to support its implementation. With increasing water scarcity and the need for sustainable water management practices, DPR has the potential to play a critical role in securing water supplies for communities around the world.

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CHAPTER 2: DEMONSTRATION OF POTABLE WATER REUSE AT UMNGENI-UTHUKELA WATER

2.1 INTRODUCTION

uMngeni-uThukela Water (UUW) is a state-owned entity, legislated to provide potable water and other related services in KwaZulu-Natal. The oranisation's vision is to be a '"Global leader in the sustainable provision of water and related services" (uMngeni-uThukela Water, 2021). In line with providing a sustainable solution to water scarcity, research into direct potable reuse was initiated. Laboratory and bench scale projects paved the way for the development of the current, full-scale direct potable reuse project. Previous projects were conducted by UUW to test the viability of direct potable reuse. The aim was to test a range of advanced treatment technologies in different combinations and to establish a preferred reclamation treatment process train for the Darvill Wastewater Treatment Works (WWTW) in KwaZulu-Natal. One of these projects was research focused on identifying the most effective and cost-efficient water reclamation processes for producing potable water from domestic wastewater effluent, and was funded by the Water Research Commission (WRC) (Report No. K5/1894) (Metcalf, et al., 2014). The study tested various treatment technologies in different combinations, aiming to meet both South African and international drinking water standards.

The research was conducted in two main phases. The first phase included the bench-scale evaluation of advanced water treatment technologies, with membrane bioreactor (MBR) technology as a pre-treatment step, followed by ozonation (O_3), granular activated carbon (GAC), nanofiltration (NF) / reverse osmosis (RO), and advanced oxidation (using hydrogen peroxide and ultra-violet (UV) radiation) were tested. The main objective of the first research project was to evaluate the performance of a range of configurations of advanced water treatment technologies, with a membrane bioreactor (MBR) as the pre-treatment step to produce potable water. The important criterion was that product water quality derived from the reclamation process should meet both South African and international drinking water standards. Advanced water treatment is required for potable water reuse as secondary and tertiary treatment will not produce a water of sufficient quality to comply with drinking water standards (Metcalf, et al., 2014).

In the second phase, the integration of MBR technology with advanced treatment processes was studied and the authors suggested a suitable treatment train for a full-scale water reclamation plant and provided cost estimates for capital and operation. The key findings reported by the authors presented significant insights into water treatment for reclamation. Most of the treatment methods evaluated successfully achieved the minimum water quality standards by effectively eliminating *E.coli*, reducing trace organics by over 96% and reducing CECs (including endocrine disruptors and pharmaceuticals). During process evaluation the MBR-RO-UV process were found to be as efficient as the more complex MBR-O_3/GAC-NF-UV process, which makes it more advantageous in terms of cost effectiveness. Nevertheless, membrane-based processes incur additional costs associated with brine disposal. Therefore, these processes are more viable in coastal areas but poses a significant challenge for inland regions. Hence, the authors recommended a combination of O_3/GAC treatment processes and ultrafiltration (to replace NF) due to their consistent quality and adaptability to fluctuating water quality needs. The reports for this WRC study are available on the WRC website for further detailed reading (Report No. 1894/1/14 and TT 611/14).

The results of the laboratory and bench-scale studies informed the overall design of the demonstration plant to produce 2 ML/day of potable water compliant with SANS 241: 2015 Drinking Water standards. It also evaluates the potential of available technologies as an option to meet growing water demands within its supply area. The Advanced Oxidation Process (AOP) uses ozone and hydrogen peroxide. Ozone is able to inactivate pathogenic microorganisms such as giardia lamblia, viruses, cryptosporidium parvum *(*at high doses and with long contact times), and destroys several taste and odour causing compounds in water. The AOP (ozone combined with hydrogen peroxide) is able to produce highly reactive hydroxyl radicals that degrades organic compounds (Metcalf, et al., 2014). A set of static mixers, known as the Pro3mix reactor, was also selected for aiding in mixing and extending contact time when ozone and hydrogen peroxide is dosed. GAC filters were chosen as they were found to have an extremely high specific surface area and the activated carbon media an affinity for organic molecules and proved to work effectively in the previous studies. Ultrafiltration (UF) membrane technology was chosen over the previous studied membranes such as NF and RO membranes. UF membranes do not incur the additional cost of brine treatment and disposal that RO would require.

The appropriate selection of unit operations and implementation of a multi-barrier approach aligned the process with the treatment objectives. These objectives included reduction of total organic carbon (TOC), removal of toxic substances and the reduction of inorganic nutrients. A study report from the engineering company responsible for the process design and installation of the plant indicated that the UF is effective in removing algae bacteria, viruses and certain organic components, such as colour, while GAC is capable of absorbing various types of dissolved organic matter. Hence, the combination of these three process unit operations (UF, GAC and AOP) were identified as the workhorses of the multi-barrier ATP that enable the production of potable water, that meets SANS 241: 2015 standards, when coupled with chlorination. Metcalf, et al. (2014) mentioned that if the MBR-O_3/GAC-UF-UV process can meet the TOC standard (< 3 mg/L) at the Goreangab Water Reclamation Plant then the proposed process train for Darvill Final Effluent Reuse Demonstration Plant (FERDP) has great potential to meet the objectives for a direct water reclamation plant. The final disinfection process for the FERDP that was chosen was post-chlorination via onsite generation of sodium hypochlorite. The performance of a UV dosing system will also be evaluated at the Darvill FERDP. However, the system will be installed at a later stage in the project and therefore is not included in the scope of this research study.

2.2 DESCRIPTION OF THE FINAL EFFLUENT REUSE DEMONSTRATION PLANT (FERDP)

The 2 ML/d FERDP consists of a conventional and advanced water treatment plant (ATP). The conventional process, also referred to as the "High Pressure (HP) Wash Plant", includes coagulation, flocculation, lamella clarification and rapid gravity sand filtration. The ATP consists of ultrafiltration, advanced oxidation using hydrogen peroxide and ozone, granular activated carbon (GAC) filtration and on-site electrolytic chlorination (OSEC) for disinfection of the final water. An innovative reactor design, the Pro3mix system (manufactured by Wedeco/Xylem), is used for AOP. The AOP utilises hydrogen peroxide (H_2O_2) and ozone (O_3) dosing. AOP has advantages of oxidizing difficult organics while reducing bromate formation. The treated water is stored in a 0.6 ML reservoir for supplying process water to Darvill WWTW. The HP Wash plant and ATP are fully automated with several dedicated sampling points and online analysers to allow for ease of optimization and troubleshooting at each unit process.

The overall process flow diagram for the FERDP is shown below in Figure 2-1. As depicted in Figure 2-1 below, the ATP has been designed with treatment flexibility to accommodate two process configurations:

- Process Configuration No. 1: AOP (H_2O_2/O_3 dosing) > GAC Filtration > UF > OSEC
- Process Configuration No. 2: UF > AOP (H_2O_2/O_3 dosing) > GAC Filtration > OSEC

It is important to note that the above two process configurations for the ATP do not run parallel to each other.

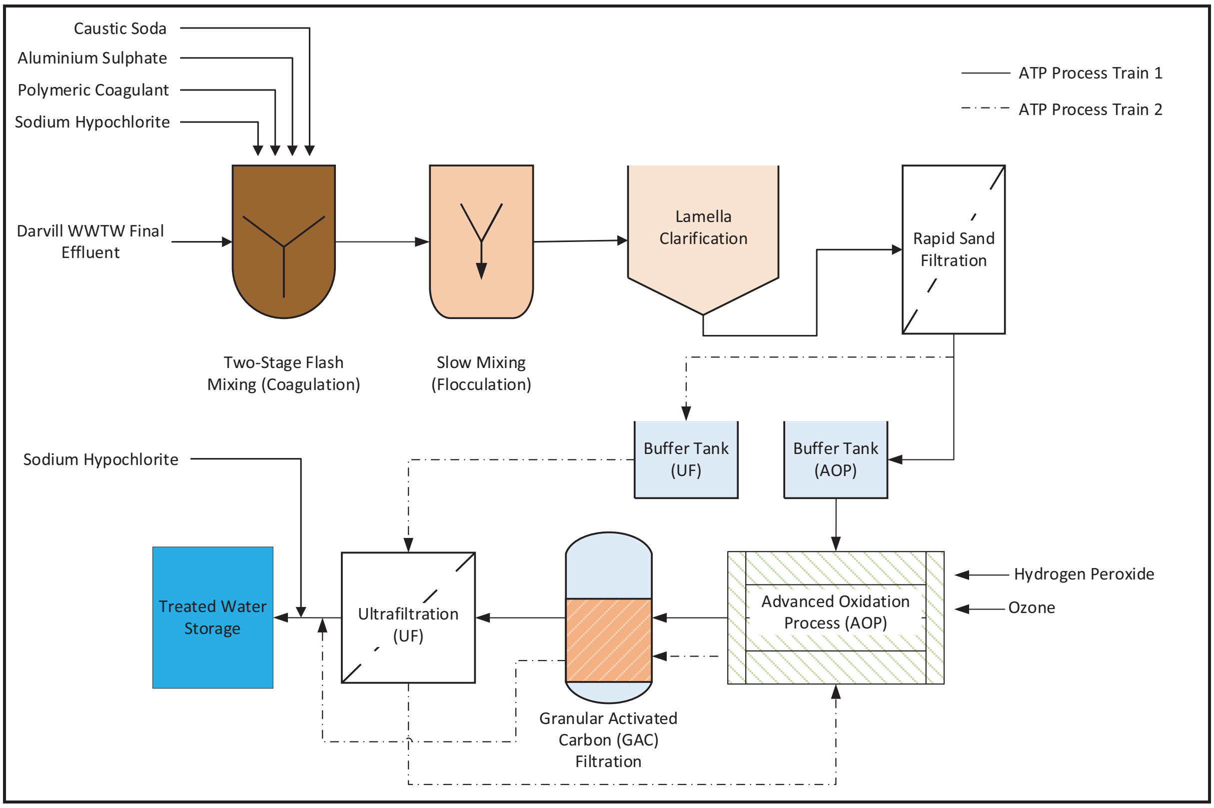

Figure 2-1: Process Flow Diagram of the Darvill Final Effluent Reuse Demonstration Plant.

2.2.1 Conventional Treatment Process

The conventional treatment processes at the HP Wash plant consists of coagulation, flocculation, lamella sedimentation, and rapid gravity sand filtration.

2.2.1.1 3.2.1.1 Coagulation

The coagulation process involves two-stage flash mixing to disperse the coagulant within the feed water. Application of a coagulant assists in destabilizing a colloidal suspension, causing colloids to agglomerate and form flocs. The best performing coagulant, as well as the optimum dose, was determined upon the results of a series of jar tests. After the coagulant is added, rapid or flash mixing ensures uniform dispersion of the coagulant throughout the basin using vertical shaft mixers. The coagulants dosed are aluminium sulphate and a polymeric coagulant. Provision has also been made to dose sodium hydroxide (caustic soda), in the event that pH control is required to promote effective coagulation and flocculation.

2.2.1.2 Flocculation and Sedimentation

Following coagulation, the flocculation process assists in forming flocs. In contrast to the coagulation process, the flocculation process involves slow mixing to enhance the contact between the coagulant and the feed water for the subsequent formation of flocs. Vertical shaft mixers are used for the flocculation process. After the water is coagulated and flocculated, it moves into the lamella-type sedimentation basins to remove the flocs.

2.2.1.3 Rapid Gravity Sand Filtration

A rapid gravity filtration process that consists of three dual-media (gravel support and sand filter media) filters is used to trap the flocculated water to provide a filtered water turbidity of less than 1 NTU. Parameters used for the filter design include filtration rate (14.5 m·h^{-1}), effective size of filter media (gravel 3-5 mm, sand 0.9 mm), filter media depth (gravel 1.5 m), and available net head (1.8 m). During the filtration process, suspended matter is accumulated in the filter media bed between sand grains. The filter is backwashed when the head loss exceeds the available head or increased turbidity is displayed in the filtrate. Air blowers operate by developing a pressure differential to move air between the entrance and exit points.

The backwash process consists of four stages as follows:

1. Air scour – Filter media bed is declogged (3 minutes);
2. Water and air – Trapped particles are removed from the filter media bed (10 minutes);
3. Water only – Filter media bed is rinsed (5 to 10 minutes); and
4. Rest time – Filters are allowed to 'rest' before it goes back into filtration mode (5 to 10 minutes).

The filters are set to backwash once every 24 hours; however, the filter backwash frequency and duration can be adjusted on SCADA. The filtered water is stored in two concrete tanks (i.e. buffer tanks) for temporary storage and buffering between the HP Wash plant and ATP, with level transmitters serving as the control interface between the two plant sections.

2.2.2 Advanced Treatment Process

The main objectives of the advanced treatment plant (ATP) is to reduce organic carbon to a minimum. This would remove biodegradable material which could cause downstream biological growth problems, and which could also lead to taste and odour problems. The ATP will also remove toxic or harmful substances and reduce inorganic nutrients to avoid downstream problems such as biological growth. Most importantly, it will provide multiple barriers to the passage of bacteria and viruses so that pathogens are eliminated from the product water; hence, clear, colour-free, safe to consume and palatable water that conforms to the current SANS 241: 2015 drinking water standards will be produced. To achieve this, the ATP process has been designed to allow the operation of the ATP using either one of two process configurations, namely; process configurations No. 1 and No. 2 as presented in Figure 2-2 and Figure 2-3, respectively.

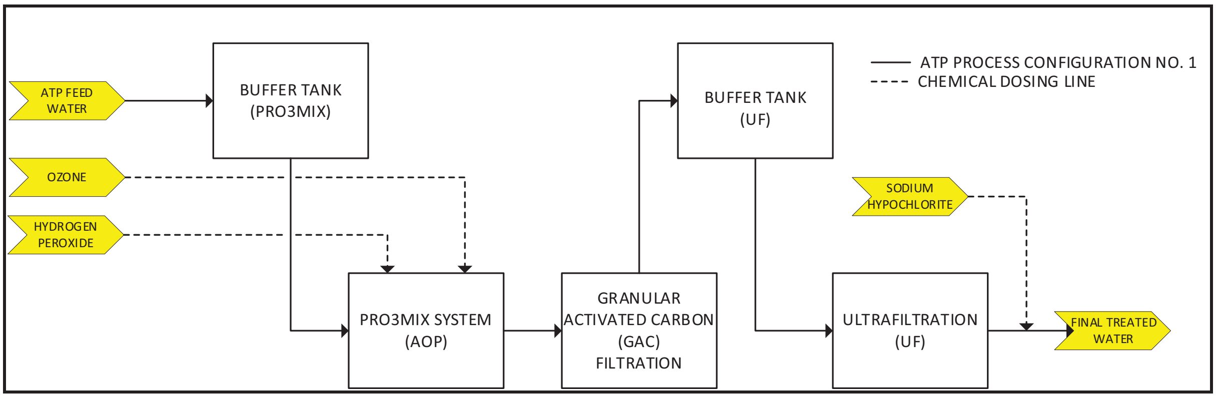

Figure 2-2: ATP Process Configuration No.1

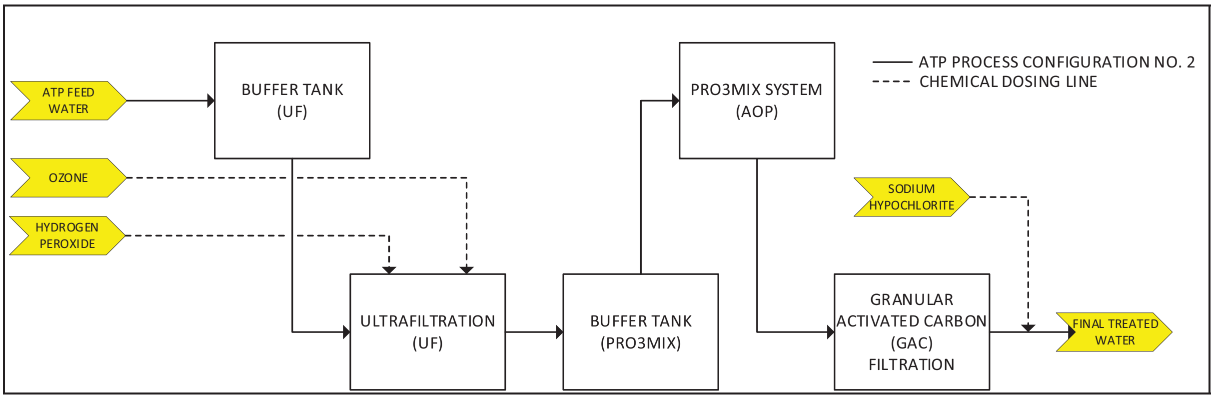

Figure 2-3: ATP Process Configuration No. 2

The process is designed such that the process operator on site can select which process configuration to run using SCADA. Although switching between the two process configurations is fully automated, the process operator will have to ensure the correct buffer tanks are selected to feed water into the ATP. Lastly, it must be noted that the system has been designed such that the ATP can be manually bypassed. This allows for continuous supply of partially treated process water to Darvill WWTW in the event that the ATP is offline.

For configuration No. 1, the ATP feed water is drawn off from the buffer tank for the Pro3mix system. The water is passed through the AOP (H_2O_2/O_3), GAC filtration and UF. The UF filtrate is disinfected in line using sodium hypochlorite generated by the OSEC unit. The combination of these processes is capable of reducing concentrations of organic compounds, pathogens and CECs in the water. AOP is one of the most effective ways of inactivating pathogens and degradation of a wide range of organic compounds. The outflow from the AOP is treated in the GAC filters whereby dissolved organic matter is removed through adsorption. The UF unit further polishes the filtrate from the GAC filters by removing any excess micro-carbon particles and microorganisms. The UF filtrate is then disinfected using OSEC and stored in a 0.6 ML reservoir for supplying process water to Darvill WWTW.

The ATP feed water for configuration No. 2 is drawn off from the buffer tank for the UF system. The water is passed through the AOP (H_2O_2/O_3) and GAC filtration. The GAC filtrate is disinfected in line using sodium hypochlorite generated by the OSEC unit. The suspended ozone-depleting organic compounds is removed via ultrafiltration, therefore a lower ozone demand and thus lower ozone dosage rate is expected in comparison to process configuration No. 1. However, micro-carbon particles and micro-organisms which might be present in the GAC filtrate will have an undesirable impact on the quality of the outflow; hence, frequent backwashing of the GAC filters will be required. The final chlorinated water is stored in the 0.6 ML reservoir.

2.2.2.1 Advanced Oxidation Process

The advanced oxidation process (AOP) takes place in the Pro3mix reactor and will be operated at optimum dosages of O_3/H_2O_2 for the removal of emerging contaminants. An ozone generator (type SMO 200) with a design capacity of 614 g O_3/h (at 8% w/w) and pressure swing adsorption (PSA) system has been installed at the FERDP and has been free-issued as part of this project scope. The ozone generator and PSA system is a stand-alone unit with its own integrated controller which governs its internal operations. An ozone dosing range of 3 to 5 mg/L will be applied as prescribed by the Pro3mix supplier. The AOP is expected to remove several types of CECs at different removal efficiencies such as > 95% of antibiotics, > 95% of hormones, 80% of pesticides, > 95% of industrial chemicals, and 50-80% of pharmaceuticals and metabolites.

2.2.2.2 Granular Activated Carbon Filtration

The granular activated carbon (GAC) filters will be used to remove dissolved organic matter through adsorption. The GAC plant has two trains installed, each consisting of two vessels in series, as shown in Figure 2-4. Each unit has a bed depth of 5 m, empty bed contact time of 4.7 minutes and hydraulic loading rate of 16 m/h. Furthermore, the flow orientation can be changed so that the feed enters GAC filter No. 2 and GAC filter No. 4 and bypassing GAC filter No. 1 and GAC filter No. 3. The GAC packed column in these filters are expected to remove several types of CECs at different removal efficiencies such as > 90% of antibiotics, > 90% of hormones, 80% of pesticides, > 90% of industrial chemicals, and > 90% of pharmaceuticals and metabolites through adsorption.

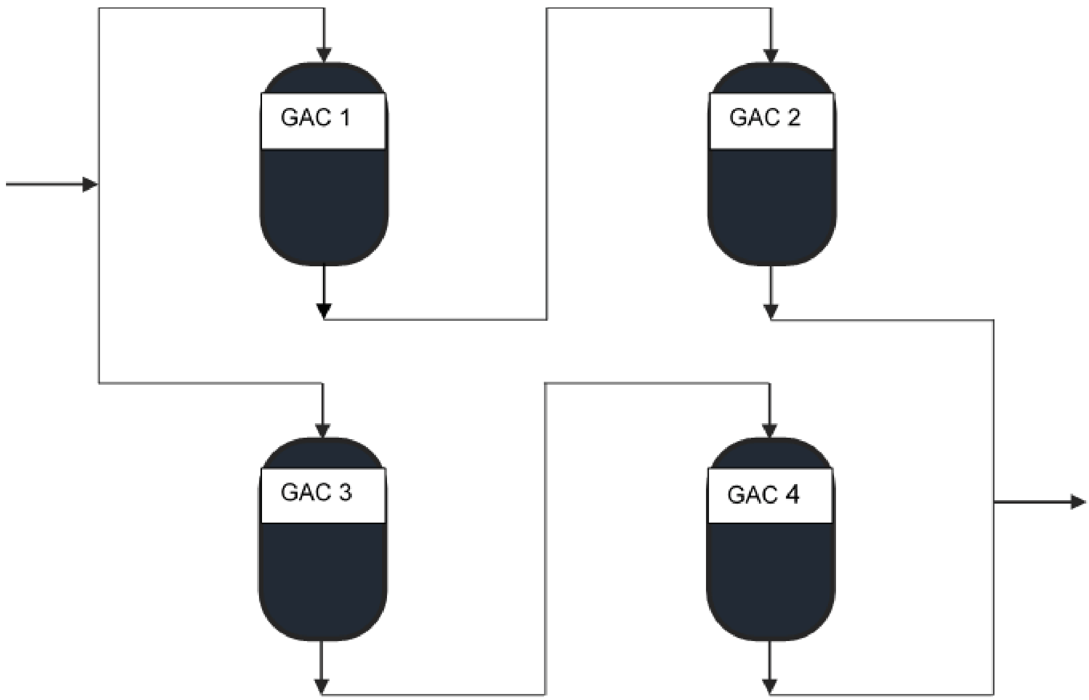

Figure 2-4: Configuration of the GAC Filters

2.2.2.3 Ultrafiltration

The installed ultrafiltration (UF) skid is a MEMCOR® CPII system arranged as 2 x 1 ML/d units, each with 20 membrane modules (i.e. 40 modules in total). The feed strainer has an aperture of 150 microns and it is self-cleaning. The UF configuration is illustrated in Figure 2-5. The UF modules operate on an outside-in principle with an active area per membrane of 66.98 m^2 and an instantaneous operating flux of 33.8 LMH. Backwash mode is set to occur after a 60 minute run-time. The normal backwashing operation is comprised of low-pressure air scouring (40 kPa for one minute), high-pressure reverse flow (~ 91 m^3/h) and forward flush (~ 91 m^3/h). The displaced backwash water is then allowed to drain. In addition, chemically enhanced Clean-In-Place (CIP) processes are used to clean the membranes of the UF system thoroughly. The CIP processes used are referred to as primary CIP, which occurs once a week, and secondary CIP, which occurs once a month. Primary CIP uses sodium hypochlorite (obtained from suppliers, not from the OSEC) whereas secondary CIP doses citric acid followed by sulphuric acid. Citric acid is a chelating agent often used to maintain UF membranes, as it is well suited to remove inorganic contaminants such as manganese, iron and aluminium.

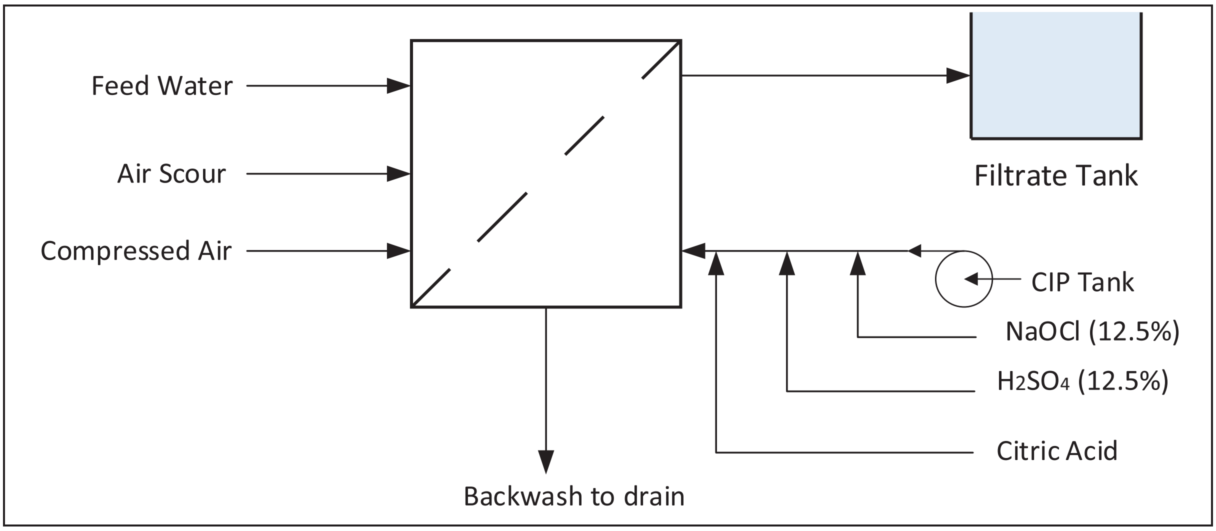

Figure 2-5: Schematic of the UF System

Sulphuric acid further assists in lowering pH levels, which decreases the solubility of the inorganic contaminants. The CIP processes comprise of the following steps:

1. Normal backwash process (as described above);
2. Water fill of membrane modules;
3. Chemical dosing (sodium hypochlorite, citric acid and sulphuric acid);
4. Recirculation and soak for 25 minutes (occurs 4-5 times);
5. Drain UF system;
6. Normal backwash process (occurs 1-3 times); and
7. Rinse to waste (5 minutes).

The UF process is also expected to remove several types of CECs at different removal efficiency such as > 90% of antibiotics, > 90% of hormones, 80% of pesticides, > 90% of industrial chemicals, and > 90% of pharmaceuticals and metabolites.

2.2.2.4 On-Site Electrolytic Chlorination

Final water disinfection will be accomplished through on-site electrolytic chlorination (OSEC). The B1-150 OSEC system, which is capable of producing an output of 8 kg/day equivalent chlorine, is installed to insure that the desired dosing concentration for sodium hypochlorite is met for final water chlorination. OSEC was the preferred method of disinfection as sodium hypochlorite (NaOCl) applied in liquid form is a safer alternative to the use of gaseous chlorination. The OSEC will generate sufficient sodium hypochlorite to achieve a maximum dosing concentration of 5 mg/L, with an operating concentration expected to be 3 mg/L. Final chlorinated water is stored in the 0.6 ML reservoir.

2.3 PROJECT AIMS

The overall aim of the Darvill Final Effluent Reuse Demonstration Plant (FERDP) is to produce 2 ML/d of water that meets SANS 241: 2015 potable water requirements using a multi-barrier process approach implemented in the plant design. The outcomes of this study will be the selection of optimized process conditions for each treatment technology for the effective removal of microorganisms and emerging contaminants. This will include quantifying the lifecycle costs and developing operational and maintenance, water quality monitoring and public engagement plans.

The following were the four main aims of the project:

1. To investigate the effectiveness of the treatment technologies at the Darvill FERDP for the removal of physiochemical and microbiological water quality determinants, as well as selected pharmaceutical compounds and contaminants of emerging concern (CECs).
2. To identify the challenges with commissioning, operations and maintenance of the Darvill FERDP and make recommendations for water entities considering implementation of direct potable water reuse to alleviate water scarcity.
3. To assess the overall lifecycle costs and make recommendations for the implementation of a full-scale direct potable reuse plant.
4. To develop public engagement and dissemination plans for a direct potable reuse plant.

2.4 SCOPE OF WORK

This research study included several key steps to investigate direct potable reuse. A detailed literature review was conducted to explore the technology overview, recent case studies, associated concerns, characterization techniques, process control and monitoring, operational philosophy, life cycle costing methodology, recommended online analysers for process monitoring, and other relevant topics.

2.4.1 Installation and commissioning

Construction, manufacturing, installation and testing of systems and individual equipment were conducted according to specific standards such as the South African National Standard (SANS), relevant international standards and/or an internal standard by the company/client. Commissioning is conducted according to the specified framework consisting of 4 stages (Hatch, 2018).

2.4.2 Development of a Water Reuse Safety Plan

Once the installation and commissioning of the plant was complete, a Water Reuse Safety Plan (WRSP) was developed. The WRSP was used in formulating the water quality monitoring programme and highlighted potential hazards to consider during the operation of the process, during the evaluation of Aim 1. As part of implementation of the WRSP, water quality analyses parameters, including turbidity, pH, free chlorine, iron, manganese, heavy metals, total organic carbon, *E. coli*, total coliforms, coliphages, nitrates, ammonia, and total suspended solids were monitored on a two-hourly, daily or weekly basis. CEC analyses, including a range of pharmaceutical testing were conducted at various stages of the FERDP process. Overall, this research approach provided a framework to investigate DPR, with a focus on ensuring water quality and the removal of emerging contaminants from the plant. The approach used in addressing the components in the project aims and limitations is discussed below.

2.4.3 Technology Evaluation

The primary objective of this research was evaluating the effectiveness of the advanced treatment processes, and the study focused on the system's ability to remove microorganisms and certain contaminants of emerging concern (CECs) from the incoming water. The contaminants investigated included different pharmaceuticals such as antiviral drugs, antiretrovirals, antibiotics, statins, antihistamines, antihypertensive, anticonvulsants and others, antiparasitic drugs, alfuzosin and biperide. To this end, water samples were collected from key sampling points (prior to treatment, following each treatment stage, and in the final treated output) and analysed against water quality standards. The findings from this investigation were detailed in Chapter 5.

2.4.4 Lifecycle Costing

To assess the overall lifecycle costs and make recommendations for the implementation of a full scale direct potable reuse plant. The protocol to conduct the life cycle costing analysis (LCCA) for the Darvill FERDP was as follows:

- Record all capital expenditure costs for the plant.
- Note power usage data and costs where possible for the various equipment.
- Document the chemical usage data on stock sheets daily and determine consumption costs for all treatment chemicals.
- Consider maintenance costs incurred.
- Include costs for laboratory services based on water quality testing conducted as per the monitoring programme.
- Consider human resources cost based on personnel required for operation of a direct potable reuse plant.
- Conduct LCCA using the present-value method and discount costs for a 20-year economic life.
- Perform a sensitivity analysis and scenario analyses on the components for the LCCA to determine which parameters strongly influence the project life cycle cost. Consider changes in economic assumptions such as the discount rate, inflation rates and energy use charges.

2.4.5 Operation and Maintenance

The second aim of the study was to develop practical operational and maintenance plans for a direct reuse plant.

- The required level of skill to operate, maintain and provide technical support were investigated. This would envisage a development of Standard Operating Manuals (SOPs) for operator training on direct potable reuse plants. This addressed gaps in the existing operator training and certification.
- Development of maintenance plans for the FERDP. The maintenance plan incorporated specific requirements for redundancy of facilities enabling individual treatment units and equipment to be taken offline for maintenance in order to achieve consistency, operational support, public health protection, and risk reduction.
- Use of a computerised asset management system can be scheduled to track the frequency of preventative maintenance, anticipated life of equipment, and record of breakdowns. This assisted in supporting the long term operational success of a FERDP.
- Collection and analyses of operational data. This was conducted to understand common failure modes at the reuse facility and the impacts on water quality that would allow for a more effective process design of resilience strategies.

2.4.6 Public Engagement and Dissemination

A public engagement strategy was developed for the water reuse facility, aimed at addressing community concerns and misconceptions about water reclamation. This aimed to foster buy-in and support across a diverse group of stakeholders, ranging from school children to policy makers. The strategy's main goal was to enhance understanding and acceptance of water reuse practices, contributing to the expansion of the water reuse network within the sector. This effort included the establishment of the KwaZulu-Natal (KZN) Water Reuse Chapter to further these aims. The project's findings were shared at both local and international forums and conferences (Water Reuse National Forum, WISA, IWA Water Reuse conference), to disseminating knowledge and best practices. This dissemination effort extended to capacity building, with a specific emphasis on nurturing the next generation of experts through training programs for postdoctoral researchers, PhD candidates, and Master's students. UUW, in an effort to advance knowledge on emerging contaminants, set up a collaborative research chair in partnership with the University of Pretoria, focusing on the study of three emerging classes of chemicals.

2.5 PROJECT LIMITATIONS

The study faced several limitations that influenced the scope of the project. Primarily, the plant was operational in only one of its intended configurations (process configuration No. 1; HP Wash followed by AOP (H_2O_2/O_3 dosing) > GAC Filtration > UF > OSEC) for the majority of the study, due to delays in the full handover process. This limitation hindered our capacity to fully assess and optimize both envisaged process configurations. Furthermore, the analysis of contaminants of emerging concern (CECs) was restricted by the analytical capabilities available within South Africa. This limitation necessitated a focus on specific CECs, leading to selection based on their prevalence and the availability of detection and quantification methods, and also resulted in delays due to the need to send samples abroad for analysis. It is critical to develop local human capacity and in-house analytical methods to enhance the frequency/scope of analysis and dependability of data.

Additionally, while certain data was available from the operation of the FERDP, the Life Cycle Costing Analysis (LCCA) was predominantly based on theoretical assumptions and estimations, a reflection of the challenges posed by interruptions in plant operations. For a more robust LCCA, it is recommended to collect comprehensive operational data once the plant is fully functional. This would involve the installation of dedicated meters to monitor the plant over a 6 to 12 month period in full operational mode and conducting a more detailed sensitivity and scenario analysis that incorporates real plant data.

Due to these limitations the report presents summarised, pertinent information relating to the results obtained and the Life Cycle Costing Analysis.

CHAPTER 3: INSTALLATION AND COMMISSIONING

3.1 INTRODUCTION

Two subcontractors were involved in the installation and commissioning of the FERDP. This led uMngeni-uThukela Water and the main contractor to closely follow and monitor tie-ins to ensure that the accountable parties took responsibility for their specific portions of work within the scope. This was important since issues arose due to subcontractors working in isolation with overlapping work, which indicated the need to have an integrated multidisciplinary platform. This chapter discusses the challenges during construction, installation and commissioning of the FERDP, as well as the quality assurance and safety aspects, completed commissioning activities, lessons learnt and future work.

3.2 CONSTRUCTION PHASE OF FINAL EFFLUENT REUSE DEMONSTRATION PLANT

During the construction phase, modifications to the project scope were proposed and are listed below:

- Change in valve casting material

According to uMngeni-uThukela Water specifications, ductile iron must be used for check valves. Due to material unavailability, a request was made to use cast iron instead of ductile iron. Cast iron was readily available and would not result in a long delay time. Ductile iron can be bent without breaking, whereas cast iron is brittle and breaks when bent. For check valves that are frequently utilized it is important to utilize durable materials. Hence; the contractor was informed to check with other client-approved suppliers or apply for a concession.

- Installation of ventilation fan in the Onsite Electrolytic Chlorination (OSEC) room

Sodium hypochlorite is generated in the OSEC room and as such there was a request for an additional and independent ventilation system for the OSEC room. A fan that is separate from the OSEC unit was to be installed on the outer wall of the room. This was to ensure that air would continuously blow out of the OSEC room to minimize the risk associated with potential hydrogen gas release.

- Change in material of specified interconnecting pipes outside FERDP

It was proposed to change the material of the two interconnecting pipes outside the FERDP building (the UF system permeate to final water line, the GAC system filtrate to final water line and the final water line) from stainless steel to polyvinyl chloride (PVC). The contractors proposed that PVC was the better option since the plant runs on a start/stop mode and not continuously; hence, the chlorine would damage the passive layer and start to form crevices. PVC would also reduce costs and the lead time. This proposal was not accepted and stainless steel was used.

- Two different design codes were used in the fabrication for vertical air receivers

An application for concession was made since two different design codes, American Society for Mechanical Engineers (ASME) and PD 5500, were used in the fabrication of the vertical air receivers. The manufacturer stated that from experience, it was found that vessels under 900 mm in diameter are more economically viable to design according to ASME standards whereas above 900 mm, the PD 5500 standards are more viable. This concession was approved.

Construction for this plant was delayed and the main cause was the downturn in the construction industry after the FIFA World Cup in 2010. The main contractor for this project went into business rescue and as such, an 18-month delay in the project occurred prior to the COVID-19 pandemic. Contractual issues also meant that new subcontractors were required to complete construction. uMngeni-uThukela Water did not have procedures readily available for when a contractor goes into business rescue before a project is complete and each project has to be evaluated on a case-by-case basis. Due to the complexity of the Darvill WWTW Upgrade project, this resulted in lengthy delays and legal procedures.

3.3 QUALITY ASSURANCE

Construction, manufacturing, installation and testing of systems and individual equipment were conducted according to specific standards such as the South African National Standard (SANS), relevant international standards and/or an internal standard by the company/client. The following are some of the standards and codes that are used[1]:

- ISO 9001 – Quality Management System
- SANS 51278 – Chemicals Used for the Treatment of Water Intended for Human Consumption (Ozone)
- SANS 50902 – Chemicals Used for the Treatment of Water Intended for Human Consumption (Hydrogen peroxide)
- SANS 50937 – Chemicals Used for the Treatment of Water Intended for Human Consumption (Chlorine)
- API 1104 – Standard for Welding Pipelines and Related Facilities
- ASME B31.3 – Process Piping
- ASME B31.4 – Pipeline Transportation Systems for Liquids and Slurries
- SABS 1200 – Standardized Specifications for Civil Engineering Construction
- SANS 1123 – Pipe Flanges
- SANS 9606-1 / ISO 9606-1 – Approval Testing of Welders
- SANS 17640 / ISO 17640 – Non-destructive Testing of Welds
- SANS 15609 and SANS 15614 – Specification and Qualification of Welding Procedures for Metallic Materials
- Water Industry Mechanical and Electrical Specifications
- uMngeni-uThukela Water Internal Specifications for Engineering, Product/Suppliers, Equipment and Approvals
- Valve specifications according with DWS 2510

Quality Assurance (QA) is essential to all parts of a project and the following are required as part of the QA process:

- Approved drawings
- Approved method statements – Details the method by which the contractor intends to handle and execute the task given and must be approved by engineer/client before work can commence on site.
- Approved Quality Control Plans
- Approved data sheets
- Approved Welding Procedure Specifications and Procedure Qualification Records

A Quality Control Plan (QCP) is essential for manufacturing and installation. It indicates all the intended activities and tests that will be conducted as well as the control measures that will be used during manufacture, independent quality surveillance and testing by the client. QCPs should state the specifications, procedures, codes and standards that apply to specific activities, the criteria that shall be used for acceptance and the records required. QCPs are important for any project as issues may arise if there are no control measures to accept equipment, especially those equipment that are new to the organisation and/or process. A QCP has hold points that required approval before proceeding to the next stage of manufacture. There are stages that are subject to random surveillance and inspections by the client or a third party following satisfactory

[1] This is a condensed list of standards and specifications.

verification and acceptance by the Contractor. Hold points are points at which work cannot proceed before completion of all operations, modifications and related verification activities identified after the previous hold point on the QCP (Bajoo, 2018). Once a supplier/contractor has received a signed acceptance, they can proceed beyond a hold point.

The QCP ensures that every step of the process is approved from design to final inspection so that the quality standards are adhered to, and the equipment is fit for purpose. Once the unit is approved and the Factory Acceptance Testing is completed, the unit can be released and transported to site where it will undergo Site Acceptance Testing after installation. An example of a QCP for the GAC unit is shown in Appendix B (note that some information has been omitted due to confidentiality).

3.4 TESTING AND INSPECTION

Tests and inspections were conducted by the manufacturers and contractors, and these followed the QCP for each piece of equipment. The QCP is explained in Section 3.3 where different stakeholders witness, review and verify the equipment received and installed. Testing included the Factory Acceptance Testing (FAT) and Site Acceptance Testing (SAT) that must be done for equipment. FAT was the testing done by the manufacturer on a plant item or equipment to prove that the item operates in accordance with the design specifications. SAT was performed at the final installation site of a section of plant or equipment to prove that the item meets, within an acceptable level of risk, the design specifications. This was done to ensure that no damage occurred during transportation and reassembling (Ergon Energy, 2017). An example of the FAT for the ozone generator in the ATP plant is shown in Figure 3-1. The purpose of this FAT was to verify the general functionality of the ozone system. Visual inspection of all equipment and components required for the FAT were carried out and, thereafter, a functional test was performed according to the specified set points.

Inspections were conducted for piping, electrical, instrumentation, mechanical and civil works according to the relevant QCPs. Some of the testing and inspections that were done for welds included radiographic testing, magnetic particle inspection and dye penetrant inspection tests. Inspections were also conducted for the pipes, which comprised corrosion protection, colour coding, and checking pipes and spools for cleanliness, sealing of open ends, and protection of flange faces. Hydro testing was also performed on pipe systems and the system/line was flushed as required. Once the final inspections were conducted and all stakeholders were satisfied with the results, the equipment was signed off and released with the client’s approval.

During commissioning various tests and inspections were also completed. Some of these include electrical tests on equipment, such as motors for the vertical shaft mixers, which comprised of testing the electrical connections to ensure they were correctly wired and not loose as well as insulation testing and checks on the glands to ensure that they are sealed to prevent water ingress. Rotational checks were also done for the mixers, pumps and compressor fan belts. Leak tests were performed for any equipment that water is flowing through or that will be holding water (pipes, valves, clarifiers, filters and other vessels). The rotational speed for the mixers were determined using a tachometer. Verification of dosing pump flow rates was conducted using a drop test facility. Coagulant trials were also performed before the plant start-up to determine the optimum coagulant and dosage required. The commissioning procedure will be covered in more detail in Section 3.5.

Ozone System Unit 1				
Parameter	Unit	Process Test Points		
		1	2	3
Checked by	-	JLH	JLH	
Date	-	13.12.16	13.12.16	
Time	-	8 00	8,25	
Setpoint O_3 Gas Flow	Nm^3/h	5,2	1,05	5,2
Setpoint O_3 Concentration	g/Nm^3	117	117	117
O_3 Production	g/h	614	122,8	614

Actual Value	Unit	1	2	3
Gas Flow	Nm^3/h	5,19	1,02	
O_3 Concentration	g/Nm^3	118,0	118,0	
O_3 Production	g/h	608	126,5	
O_3 Pressure (outlet)	bar(g)	1,0	1,0	
Converter Power	kW	5,55	2,1	
Cooling Water Inlet Temp.	°C	25,1	25,6	

Figure 3-1: Portion of the Factory Acceptance Test for the Ozone unit

3.5 COMMISSIONING

3.5.1 Overview

This section of the report presents the commissioning process of the FERDP, the details of each stage, the approvals and certification requirements, and the challenges experienced during the project. Commissioning is conducted according to the specified framework consisting of 4 stages (Hatch, 2018). These commissioning stages include the work that shall be carried out and the personnel required for each stage. The progress continues to the next stage if no category A or B Punch items are found after the checks for the stage have been completed. Punch items are non-conformities with the specification for the stage.

Punch List categories:

- Category A – Items on List of Defects, which are of essential and critical nature.
- Category B – Items on List of Defects, which are deviations that cannot be rectified while the plant is running but can be rectified during the next stage of commissioning and are within the contractors' scope of work.
- Category C – Items on List of Defects, which are not of critical nature and the deviations can be rectified while the plant is running but before the final plant acceptance. It should also not be essential to safety and/or process.

- Category D – Items on List of Defects subject to a contract variation order and includes items such as modifications.

The client must be a part of the commissioning throughout the process. This ensures that buy-in and handover are easier at the end of the project. If the client has a multidisciplinary team (mechanical, process, civil, electrical and instrumentation), that would be advantageous for the project. The four stages of commissioning was conducted for the ATP. Table 3-1 lists the pre-commissioning checks required for the ATP. Table 3-2 below highlights the commissioning activities that was carried out for the ozone generation unit installed at the ATP. Table 3-3 highlights the commissioning activities for the CPII UF System only (the detailed commissioning plan will highlight activities for the air panel, CIP system and CPII unit).

Table 3-1: ATP Pre-commissioning checks

Item	System	Functionality Tests/ Checks
1	Electrical	All cabling for power supply by client to motor control center (MCC), power out of MCC to FERDP and instrument cabling.
2	PVC piping	Check for cracks, broken fittings, pipe supports are properly secured, all fasteners on all flanges installed and tightened, all sensors and instruments installed, no missing components and all valves correctly aligned and working.
3	Structures	Check for signs of corrosion or cracking, all fasteners and securing bolts are present and tightened, all skids are correctly aligned, and piping is straight and level.
4	Stainless steel piping	Check that all Victaulic couplings are properly fastened and secure and all fasteners on all flanges complete and tightened.
5	Instruments	Check that all instruments are properly fitted and connected to the relevant transmitters and Instrument Air Pressure where relevant.
6	Motors	Check all motors and drives, voltage rating and supply voltage, connections (drive belts or flex connectors), rotation. Check entire electrical system, terminations, MCC design and layout as per drawings, conductivity, lock outs and switches, insulation on cables and motors, earthing.
7	Tanks	Tightness tests to check for leaks.
8	Set-point	Set-point checks for all ATP equipment.
9	Chemical dosing	Verify pump dosing rates and visual inspections.
10	Manual operation: Pumps	Prime pumps, verify pump direction, set variable speed drive (VSD) parameters and test alarms.

Table 3-2: Ozone Generation Unit Commissioning Activities

Item	System/ Process	Functionality Tests/ Checks
1	Mechanical	Installation checks.
2	Electrical	Installation checks.
3	Applying voltage to the system	Electrical connections.
4	Cooling water	Level of cooling water in cooling water circle (chiller, closed loop, cooling water piping) and check condition of cooling water.
5	Feed gas	PSA: Initialisation start sequences – Compressor and PSA to run in for minimum 24 hours (in bypass mode); after regeneration operate ozone generator with generated air. Dryer unit: Initialisation start sequence – to run from 4 to 8 hours (in bypass mode); after regeneration operate ozone generator with dried air.
6	Process parameters	Pre-set operating parameters, with touch panel adjusted, are correct: purge mode, power limit and gas flow regulation. Catalytic Ozone Destructor in function. Process water continuously available from client.
7	Purge mode	Ensure that all components function properly (e.g. pump/injection system) and start up the ozone generator in purge mode without converter power (converter = 0%).
8	Final “pre-commissioning” check	Final mechanical, electrical and process engineering (gas flow regulation, pressure and regulation parameter) checks.
9	Safety check	Emergency shutdown procedures and ambient ozone/oxygen monitoring.
10	Final start-up	Switch of the operation mode from “automatic mode” into “hand mode”: Set converter power to 0%. Engage/switch on converter power and move “converter power” from 0% to next level slowly (25, 50, 75 and 100%) and check for leakage and noise. Perform final visual and acoustic checks.
11	Pre-work for performance test	Ozone generator/system is in operation and works with 100% converter power. Switch off the operation mode from “automatic mode” into “hand mode”. Execute performance test with “performance test form”.
12	Final Acceptance Test & Handover	Client in authority to attend personally during the final acceptance. Complete the acceptance form and to sign off and handover copy of service report and certificate of completion to client.

Table 3-3: CPII UF System Commissioning Activities

Item	System/ Process	Functionality Tests/ Checks
1	Pre-commissioning checks	Verify pre-commissioning checks on all relevant documentation, valves, pipes, and pumps.
2	CPII Feed System Control	Low-level shutdown, feed pumps duty/standby rotation operates correctly. If a duty pump faults during operation, the standby pump starts.
3	CPII Feed Manifold Pressure Control	Pressure setpoints, feed pressure setpoint algorithm works correctly and feed manifold pressure low and high shutdown setpoint is set up and operates correctly.
4	CPII Compressed Air System	CPII System shuts down on loss of plant control air and loss of plant process air. Compressors operates cut in/cut off correctly. Air Compressor duty/standby rotation operates correctly, changing duty after each start. If a duty compressor faults during operation, the standby starts.
5	Backwash Waste System	If the water level is above the setpoint and not able to receive water, the backwash resource is not granted.
6	CIP System	CIP tank fill sequence operation, heater operation, tank drain sequence, ring main flush, chlorine dosing system operation and acid dosing system operation. CIP sequence operation with acid and sequence operation with chlorine. Acid Maintenance Wash (MW) sequence operation and chlorine MW sequence operation.
7	Neutralisation System	If the neutralisation tank is above the setpoint and not able to receive water, the CIP Rinse Resource is not granted.
8	CPII System Start-up	CPII system starts on receipt of a plant start signal from the plant PLC and set-point at correct setting.
9	CPII System Standby	CPII Units enter into standby on receipt of the plant standby signal and manual standby/resume from filtration operates correctly. Automatic standby/resume from filtration on operates against feed tank level correctly and automatic standby/resume from filtration on operates against filtrate tank level correctly.
10	CP System Shutdown	The CPII System shuts down on loss of communications with Plant PLC, when not enough CPII Units are available and if CPII feed temperature goes high.
11	CPII System Flow Control	Maximum plant flow, automatic flow setpoint assignment by Master PLC works correctly and manual flow setpoint assignment by operator (via SCADA) works correctly. Duty rotation operates correctly.
12	CPII System Queuing	Start-up, backwash, and CIP queuing.
13	Reporting	Operational, CIP and Pressure Decay Test report per CPII Unit is generated as per the CPII system control philosophy.
14	Power failure	On CPII Master PLC communications failure, i.e. power supply to the Master PLC is turned off, each CPII Unit and the CP system shuts down.
15	PLC program	Master PLC Program uploaded/downloaded as necessary.

3.5.2 Stage 1 Commissioning – Construction Complete/ Construction Testing

Stage 1 Commissioning occurs when mechanical installation is completed, and only minor defects remain. The QCPs have been approved and all prescribed inspection, testing and Punch listing is carried out and recorded. Punch listing and facility check out are performed by the Engineer, Resident Engineer's representatives, Contractor and Client Team members. All known defects are listed and recorded in the Master Punch List. The Contractor QA/QC Manager is also required at this stage to oversee the process. The Resident Engineer must check the plant to ensure that the construction is in accordance with the design and specification. Any defects that are detected at this stage should be minor and must not jeopardise the safety of operation. No equipment is energised at Stage 1 Commissioning and the contractor must provide red-line drawings. Process and Instrumentation Diagrams (PIDs) are required at this stage along with a control philosophy and equipment list.

Some of the activities carried out in Stage 1 Commissioning included analysing the Punch Lists to determine if the equipment shown in the PID corresponds to the equipment that has been installed on the plant. Items are checked for ease of accessibility, ease of operation and correct installation, i.e. non-return valves are installed in the correct direction. Table 3-4 below shows the results of Stage 1 Commissioning.

The installation issues that were of interest and could occur on other similar projects were as follows:

1. In South Africa it is common for electrical connections of mixer motors to be installed in a star configuration. The flash mixers were imported with a delta type (triangular) connection instead of the required star type connection. During the initial start-up, the mixers would not start properly; it would power on and phase out. After consulting with the equipment data pack, the problem was resolved, and the smaller mixer motors were reconnected using the correct configuration. An error like this can pose a risk to equipment as operating with the wrong type of connection could cause the equipment to burn out and fail. When the mixers were tested again during Stage 1 Commissioning, there was an unusual sound which indicated that the bearings were worn out and they had to be sent for repairs. Upon stripping and assessment at the supplier, it was found that water had entered the unit and caused the bearings to fail.

Table 3-4: Stage 1 Commissioning Results

No.	Item/ Section	Includes	Commissioning Results	Changes/ Modifications	Status
1	Mixers	Blades, motor and gearbox	Unusual noises during start-up and vibration during operation.	Mixers were sent for repairs. The structural support for the mixers also required reinforcements to prevent the mixers from vibrating.	Complete
2	Clarifiers	Influent penstocks, lamella plates, desludge valves	Some of the lamella plates were broken due to severe weather conditions (hail).	Install covers for the two lamella clarifiers.	Complete
3	Dosing Systems	Chemical tanks, dosing pumps, pipelines and bund area	Bund area has holes/ openings in the wall which indicates that it is not completely bunded in the case of a chemical leak. Pipes located outside in the aluminium sulphate bund area require protection (epoxy resin paint) to prevent damage.		Incomplete
4	Filters	Pumps, pipelines, rapid gravity sand filters, valves	The seals for the backwash pumps were assumed to be leaking due to an unusual noise during testing. There was leakage, probably due to worn-out seals. Impellers would not turn when switched on.	The pumps were sent for repairs.	Complete
5	UF and GAC Feeding Systems		Pressure gauges installed on site were facing the wrong direction.	Pressure gauges require change of direction to allow for ease of monitoring for the operators (to easily check the reading without obstructions).	Complete
6	Safety	All systems in the HP Wash plant and ATP.	The safety showers and wash basins need to be installed at the ATP. The showers and basins already installed need to be relocated to appropriate locations to ensure that the operators have access to them when required.	Relocated showers and basins.	Complete

There was rust present due to water ingress and one of the cam rings were damaged and required replacement. It must be noted that the mixers were also installed and not used for a long period of time and during the severe weather conditions, water ingress would have occurred. It is important that equipment is maintained from the time of installation to prevent such damage which has further time and financial implications. Communication and information sharing between the different disciplines is also important so that contractors are aware of the equipment onsite and the requirements before installation and testing occurs. It is the also the responsibility of those working with the equipment to ensure that data and equipment sheets are reviewed before starting any work.

2. The lamella plates in the clarifiers were damaged due to severe weather conditions; heat made the plates brittle and hailstorms broke some of the plates. To prevent this from occurring, the plates should be covered in water so that it would simulate normal operating conditions and prevent damage due to sun exposure.

3. It is important that bunded areas are properly closed off and do not allow for leaks into the common areas. Site run piping should not affect containment.

4. The filter backwash pumps have a valve that is used to release air and for priming. Some of the valves were already opened hence, when testing was conducted, it was assumed that the pump seal had a leak. The pumps were sent for repairs and rust was found on the inside which was subsequently cleaned. Lack of maintenance also causes equipment to not work during testing and start-up processes. It is important for those working on specific equipment to have a thorough understanding of the equipment, its parts and functionality and to do pre-test checks to ensure that the equipment is operated the correct way and prevent misdiagnosis.

3.5.3 Stage 2 Commissioning – Pre-Operational Equipment Testing / Cold Commissioning (Dry):

Stage 2 Commissioning consists of the complete inspection and testing by the Contractor(s) of each piece of equipment individually. This includes electrical control and power cabling connected to the equipment and checking the configuration and calibration of each instrumentation loop. During this phase, equipment is energised. Mechanical and Electrical engineering teams are required for this stage. Prior to this stage, the Contractor must have compiled a Contractor's data book during Check Out Acceptance. The individual equipment is tested (without product) in the presence of the full commissioning team to prove that start and stop functions are controlled. The individual responsible and accountable for the Stage 2 Commissioning is the Contractor's Commissioning Manager. The Resident Engineer must ensure that the plant has been constructed according to design and specification. The Contractor's Commissioning team actions Punch listing to ensure construction completion and will carry out inspections and witness tests and ensure that the results are recorded in the Commissioning Test Packs. Witnessing and acceptance of the test results is the responsibility of the Resident Engineer. During Stage 2 Commissioning, the Punch List may be amended to include the items that were detected only after commencement of operation. Punch List category A items for a relevant system must be completed prior to starting Stage 2 Commissioning. The Contractor Construction/Project Manager and the Client Team Representative will sign the Stage 2 Completion Certificate from the Installation Contractor(s) after Stage 2 commissioning.

The plant was divided into different systems for commissioning. This was done to facilitate commissioning since electricity to the plant was a challenge due to constraints faced by the contractor. It was decided to commission as the electricity became available to each system. Under normal circumstances, a whole process system (e.g. filters along with valves and backwash pumps) would be commissioned. Whilst the division into systems allows for commissioning to progress, there is an associated risk, that system issues may arise upon completion and tie-ins could result in further delays if repairs and modifications need to be done. Figure 3-2 shows the different systems for commissioning (Hatch, 2022).

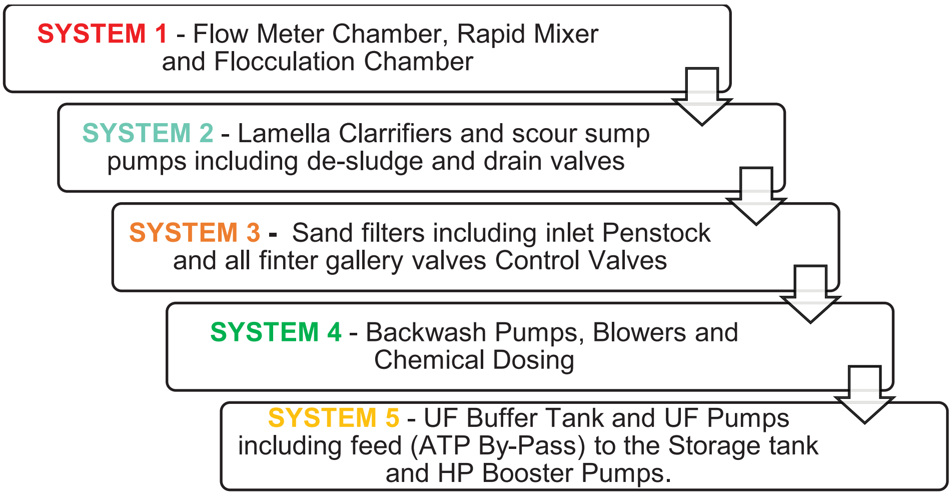

Figure 3-2: Different systems for commissioning

Table 3-5 presents equipment items that need to pass the Stage 2 Pre-Operational Equipment Testing. Potable water was used to test functionality for this stage.

Table 3-5: Tests conducted during Stage 2 Commissioning

Item	Scoped Sub-System	Functionality Test/Checks
1	Manual valves	Check open/close fully.
2	Actuated valves	Check open/close fully (local and remote manual).
3	Level and flow sensors	Check electrical power to the instrument and feedback signal.
4	Backwash pumps and blowers	Start/stop the pump and confirm rotation.
5	Drive motors (mixers and scour pumps)	Start/stop drive and confirm rotation.

System 1: The valves were able to open and close and the flow meter was operational but required calibration. Upon further inspection and assessment, it was found that water ingress occurred into the flow meter hence it was not working correctly and requires replacement. Preventative measures must be taken into account for equipment like flow meters such as installing a watertight chamber or having a sump pump to remove any water that collects. Maintenance is also important once any equipment/instrumentation is installed.

System 2: The valves were tested. Two desludge isolation valves and one of the clarifier inlet penstock valves were not completely sealing completely. Striker plates for the limit sensors were still outstanding for both penstock valves. The desludge valves were not completely sealing and requires the close limit to be reset to a lower value.

System 3: Leaks were observed on the flanges in the filter product line. Penstock valve for sand filter No. 2 trips on torque before reaching the close limit. The level sensor on sand filter No. 1 was not operational and the level sensors on sand filters No. 2 and 3 requires final setup. One of the challenges that were encountered during commissioning was determining whether the isolation valves for level control were fully sealing. This is due to the pipe configuration which means that there is a time delay for the pipe to fully drain. Design improvements should be considered for any future work in other plants. The pipe can be inclined to allow for it to empty quicker. If the quality of water is poor and is allowed to remain stagnant in the pipe for long periods of time, this could lead to deterioration and possible corrosion in the pipelines. Knife gate valves or gate valves could also be considered for isolation purposes since these valves operate well for on and off positions. However, gate valves are not quick to open and close so that should also be factored in.

System 4: The backwash pumps were tested for rotation which was in good working order. The blowers were tested; the pressure relief valve worked well, and the fan belt rotated in the correct direction. Blower No.1 failed and will be inspected and repaired. The air flow rate meter was operational. The valves for sand filters No. 1 and No. 3 did not seal completely as leaks were observed and these will be inspected, and lower limits reset.

3.5.4 Stage 3 Commissioning – Pre-Operational System Testing / Cold Commissioning (Dry)

Stage 3 Commissioning consists of testing and operation of equipment grouped together into systems. Testing is conducted with water only (if practical) using equipment modules. The Contractor's Commissioning Manager manages this stage of commissioning and will issue directives relating to Stage 3 Commissioning. All areas of the plant will be declared "Live" and a "Permit to Work" system will be implemented. These areas will be identified and clearly marked on a plot plan and displayed at the Contractor's meetings. In order to start Stage 3 Commissioning, the entire Punch List "A" and "B" items must be completed, and the Contractor is expected to provide a team for modifications and repair work. The Contractor's responsibility is to compile all Vendor data, permits, test certificates, inspection approvals, and "As-Built" information/drawings during this stage. During Stage 3 Commissioning, the Client will facilitate and complete a HAZOP 5 study, prior to commencement of Stage 4 Commissioning. The Contractor's Construction/Project Manager and the Client Team Representative will sign the Stage 3 Commissioning Completion Certificate from the Installation Contractor(s) upon the completion of Stage 3 Commissioning. An approved functional description specification and draft Operations and Maintenance (O&M) manual are required for this stage to proceed. All equipment tagging is also required for ease of operation.

This stage involved testing systems and unit processes in the HP Wash and ATP sections with potable water. Final effluent from Darvill WWTW was used for testing inlet valves and flow meter only. Table 3-6 shows the pre-operational System Checks for Stage 3 Commissioning. The system was required to operate at design capacities in order to be passed. Stage 3 Testing is conducted to prove that all the systems has been programmed as per the FDS. and potable water will be used for functional testing during this stage. Table 3-7 lists the snags that were identified during Stage 3 commissioning. During commissioning it was noted that the pumps feeding the GAC filters were too small and this caused the GAC pumps to trip often. This issue is being addressed by the contractors and new pumps will be installed. There was also the addition of a gooseneck for the GAC filters to prevent backflow and assist with the operation of the new pumps to be installed.

Table 3-6: Pre-operational System Checks for Stage 3 Commissioning

Item	Scoped System	Functionality Test/Checks
1	Inlet flow control	Initiate flow control and insert flow set point.
2	Chemical dosing	Initiate dosing control on all chemicals (turbidity, pH and streaming current detector).
3	Lamella clarifier	Initiate the clarifier de-sludging sequence.
4	Rapid gravity sand filter	Initiate sand filter level control (insert level set point for each filter bed).
5	Rapid gravity sand filter	Initiate the sand filter backwash sequence.
6	UF buffer tank	Initiate UF buffer tank selection. Confirm if correct actuator opens to the correct tank.
7	UF buffer tank and UF pumps	Initiate ATP bypass logic.
8	FERDP sump (scour pumps)	Initiate level control at the scour pumps.

Table 3-7: Snags identified during Stage 3 Commissioning

Item	System	Defect
1	Filter Gallery	• Relocate the off take for turbidity sensor at the filters. • Observed backwash rate appears too high which is a possible cause of the sand loss from the filter media bed.
2	GAC	• Extend the GAC air release valves above the final water tank. • Drive fault on GAC blower No. 2. • Air release valve (Vent-o-Mat) on the suction of the GAC feed pumps continuously draining. • Mechanical seal leaks on pumps No. 1 and 2.
3	OSEC	• Extension of chlorine dosage line to the final tank inlet from the UF buffer tank when running HP Wash plant only and ATP is bypassed. • No standby pump for brine dosing system.
4	Chemical Dosing	• Pipe supports to be fabricated and installed. • Leaks on chemical pipes. • Discharge line for disposal of spilled chemical in bund at chemical storage area (i.e. bund drainage).
5	CIP	• Add timer between CIP on SCADA.
6	Ozone Generator	• Additional ozone residual gas analyser to be installed.
7	Final Water Tank	• Power supply to the chlorine analyser at the final water tank. • Tank cleaning and disinfection required before final handover.

3.5.5 Stage 4 Commissioning – Hot (Wet) Commissioning, Practical Completion

Stage 4 Commissioning is the final preparation for plant operation. The equipment is filled with process material (final treated effluent from Darvill WWTW) and required chemical reagents, depending on the relevant systems, and the process is run according to the operating sequences. Hot (Wet) Commissioning is executed by the Contractor and Engineer. Once the plant is accepted, the Client's Operators will operate the plant, including conducting trials and safety drills. Prior to starting Stage 4 Commissioning, the entire Punch List Category B items must be completed by the Contractor(s). The Contractor QC/QA Engineer will also have prepared a Punch list of category "C" and "D" items for the Contractor which must be completed by a specified date. During hot commissioning and stabilization, the Punch List may be amended as required. Operation and maintenance are the Contractor's responsibility. The Stage 4 Completion Certificate is issued upon successful processing of material (final effluent to potable water) and acceptance by the Client Team's Manager. Performance testing is also conducted during this stage and comprises of operating the plant under various conditions, measuring the plant performance, comparing the actual performance to the design intent, and reporting the findings along with necessary corrective actions. Before handover of any unit and system training, training manuals should be completed and submitted. This ensures that the operators can accept and operate the plant. Maintenance training and equipment capitalisation is required before handover. This will ensure that the proper maintenance procedures and schedules are in place.

Stage 4 Commissioning comprised of performance testing of the ATP by the subcontractor. This was done to ensure that the desired results can be achieved by plant. Client operators also operated the FERDP during this stage and worked on a 12 hour rotational shift basis. Performance testing procedure and results from the contractor, as well as client operations, are discussed in detail in Chapter 5.

Ozone commissioning by the supplier:

- Mechanical installation checks on the ozone unit and gas piping.
- Electrical installation checks and applying voltage to the system.
- Level of cooling water in the closed loop was tested and visual checks on condition of cooling water.

- Feed gas tests were passed for the PSA.
- Process parameters: purge mode, power limit, gas flow regulation and catalytic ozone destructor, as well as checks to ensure process water from the customer is always available.
- Purge mode and the final pre-commissioning checks were done which included gas flow, pressure and regulation parameters.
- Safety checks for emergency shutdown and ozone/oxygen monitoring.
- Final steps comprised of the final start-up (check final acoustics), pre-work for performance testing and final acceptance and handover.

The following will be required to achieve completion of Stage 4 Testing and Practical Completion:

- Completion and successful commissioning of inlet flow chamber, flash mixing with chemical dosing, lamella clarifier desludging, rapid gravity sand filtration level control (including backwash sequence) and demonstration of overall functionality of the completed system in terms of the relevant functional design specification (FDS);
- Full demonstration of the ATP bypass functionality;
- Compliance with respect to documentation as prescribed in the Commissioning Framework; and
- Completion of relevant and remaining category “C” (non-critical) defects and “D” deviations.

3.5.6 Approvals and handovers

Approvals and handovers must be conducted during the commissioning process before proceeding to subsequent commissioning stages. The Ready for Commissioning (RFC) certificate after Stage 1 Commissioning is issued to the Contractor (and the Commissioning Manager) after successfully completing all relevant individual pieces of equipment, structure, pipeline, Civil portions or buildings for a specific plant area. The RFC certificate serves to handover from Construction Completion to Stage 1 Commissioning. The QC/QA Manager will ensure all Contractor’s data packs, certification, and Punch List items (category A & B) are signed off and verified by the Resident Engineer as required.

The Stage 1 Check Out Acceptance is only actioned after the equipment is installed completely (with only minor defects remaining), inspection and testing have been completed, QCPs approved, and all equipment and systems conform to the equipment design and specification. Construction completion certificates also have to be generated to each discipline by the Contractor and these include Practical Completion for all Civil and Structural Works, Mechanical Completion for Mechanical and Piping works, Electrical Completion for Electrical works, and Instrument Completion for Instrumentation, PLC and SCADA. The RFC will be issued when all above certificates are completed, red-lined O&M manual are available, and the Area/System is ready for commissioning.

The Stage 2 Completion Certificate is handed over when all Stage 2 Commissioning activities, including Punch List items (category A & B), are completed. The Resident Engineer issues this certificate to the Commissioning Manager. This certificate serves to handover the equipment and/or systems according to the contract.

The Commissioning Manager issues the Stage 3 Completion Certificate to the Client’s Team Commissioning Manager to indicate “Beneficial Occupation” or ‘Practical Completion’ by the Client and that the work has passed Stage 1, 2 and 3 Commissioning and is ready for Stage 4. All relevant documentation (PIDs, defect lists, O&M manuals and certificates) must be made available to the Client, and it is the responsibility of the QC/QA Manager. The Client team shall not operate any equipment/ systems that have not been handed over.

Stage 4 Completion Certificates comprise of the following two parts*:*

- Part 1: A certificate issued by the Client’s Team Commissioning Managers to the Client’s Team Production Managers to handover the Plant to production and optimisation after successful Stage 4

Commissioning. This certificate indicates final project acceptance in all respects of installation and performance.

- Part 2: Practical Completion (PC) Areas and systems that have been handed over to the Client are “out of bounds” to the Contractor. The Contractor must seek special permission if work has to be done in such areas. The Client activities must also be confined only to areas and systems that have been taken over from the Contractor(s). Once all commissioning and acceptance testing activities are completed and the O&M manual is completed with red-lined “as-built” documentation, the practical completion milestone is achieved. At this stage of the project the Client will have signed the Stage 4 Completion Certificates. Multiple Stage 4 Completion Certificates can be combined to support the scope as defined per PC.

3.6 CHALLENGES EXPERIENCED DURING INSTALLATION AND COMMISSIONING

Challenges in a project usually have negative effects on the budget and timeline. The following challenges were identified and highlighted for the Darvill FERDP project.

3.6.1 Project Challenges

- **Change of contractors:** Due to unforeseen circumstances, some contractors on the project changed. When this change occurred, there was no proper handover except for the Equipment List which did not include the level of progress of the work already done. This added difficulties during the preparation of new tenders since the need arose to obtain new contractors to continue the work on site and delays occurred as the process of appointing new contractors was prolonged. Procedures should be in place to ease the challenge of changing contractors. Although this is not an expected project challenge in the current economic environment, it is becoming more common.

- **Procurement:** Due to the COVID-19 pandemic, the procurement of instrumentation and other equipment from international suppliers was a challenge. Contractors and suppliers usually factor in a delay period; however, COVID-19, along with its drastic impact and national lockdowns, was unforeseen. There were delays due to material unavailability and shipping due to logistics backlog. Turnaround times increased from a few days or weeks to months.

- **Incomplete work:** The change of contractors resulted in incomplete site work. There were excavations and openings in walls made for installations that were not done. Due to the project being at a standstill when the changeover occurred, there were incidents that occurred such as flooding of certain areas. Pumps, motors, and actuators submerged in water had to be assessed and repaired or replaced. Although these were unpredicted events, proper handovers should be done before the contractor leaves and equipment that is installed must be maintained.

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- **Responsibility and accountability:** The change of contractors meant that any issues that arose from work carried out by the previous contractor would need to be fixed by the new contractors. However, the person who should take responsibility is often uncertain due to improper handover. This also leads to adverse financial implications since a new contractor has to be paid whereas the work should have been under a snag list for the previous contractor. It is important that contractors keep records of all installations and these documents must be used for handovers. The responsibility for work conducted by a previous contractor must also be clearly stipulated to and agreed upon by the new contractor before work commences.

- **Lack of communication:** Multidisciplinary projects require constant and clear communication between all contractors and the client. One of the prevalent challenges is that contractors usually work in isolation. When the tie-in of equipment has to occur, problems arise from relevant parties not meeting the correct specification which ultimately causes delays as work must be redone or modified. Although the monitoring engineer should usually coordinate this, the client needs to be involved to ensure the best possible result. This means that the client team needs both technical and project management professionals to ensure a positive outcome.

- **Incorrect equipment specifications:** Sometimes equipment is procured or built (such as the Motor Control Center panels) and does not meet the uMngeni-uThukela Water specifications. This means a decision must be made to either modify or manufacture/procure new equipment which costs time and money and further delays the projects. All contractors must be approved by the client and understand the standards and specifications of the client before manufacturing or procuring equipment.

- **Deadlines and delays:** In the event that one contractor does not adhere to deadlines for meeting certain milestones, progress is ultimately delayed for the other contractors. For example, mechanical contractors have to wait for electrical subcontractors to complete installations for equipment. This has an impact on the resource allocation and finance for the contractors and activities take longer than scheduled without any mitigations in place. It is important in such situations that a project manager must be present onsite to monitor the progress and ensure that deadlines are being met.

- **Power outages/loadshedding:** The supply of electricity in South Africa has been an ongoing challenge. Power outages and loadshedding causes delays to projects since the installation and commissioning process is affected; start-up of systems also takes time. This results in a loss of time and money. The electricity issue also affects potential installations of direct potable reuse plants in areas that lack electricity and within municipalities that cannot afford generators, since continuous operation of the treatment process will be affected. Alternate power generation methods must be used (such as solar power) if a direct potable reuse plant is to be installed in these areas. There is no backup power (generators) for the Darvill FERDP and installation of a generator unit should be considered for the future.

- **Security challenges:** Cable theft is rife in South Africa, affecting installation and commissioning activities. Replacement of cables involves downtime and negatively impacts processes. In addition to this, fittings were also stolen at the FERDP and had to be replaced. Strict security measures need to be a priority on such projects to mitigate theft.

- **Installation of equipment and lack of consistent maintenance:** Equipment that was installed but not in operation for a long period of time was not maintained and often caused problems during commissioning. Majority of the equipment installed at the HP Wash plant equipment was sent for assessment and repairs. Due to technological advancements, some of the equipment installed was obsolete and replaced with newer models (the mixer gearboxes and turbidity meters needed replacements). This results in downtime which delays the project progression and commissioning activities. Failure of equipment becomes more likely when there is lack of maintenance, and this will affect the performance of the treatment process. To mitigate this, planned maintenance schedules must be in place from the installation period of the equipment, even if it is not in operation.

- **Undefined scope:** An undefined scope causes delays in the commissioning process since it is unclear to relevant parties regarding respective scope, roles and responsibilities. Some required disciplines were not present during the commissioning process and certain pieces of equipment had no custodian. This stemmed from the change in contractors hence, it is important that even when there is a change in contractors and handovers, the scope and accountable parties should be clearly communicated and agreed upon before commencing with work on site.

- **Quality control:** Quality control protocols were not strictly adhered to during the early stages of the commissioning process. This caused delays in the project since one cannot move to the next step of the project if all quality requirements are not met. Quality control protocols must be implemented strictly on such projects to ensure that a contractor is responsible for the equipment, all inspections and tests are conducted, and records are kept.

- **New technology:** The importing and implementation of new technology, especially those sold as "black box" technology, can pose a challenge for commissioning and operation, particularly if there is a lack of local experience and expertise. Often a technician from abroad has to come to site to commission equipment and train the operators. This adds a financial cost to the project as well as delays since the plant may have to wait on the availability of the technician and training of operators before commencing with any work.

Overall, the project challenges have caused delays in meeting the intended timelines for commissioning and performance testing, which resulted in delays in the operation of the reuse plant. Since equipment that has been installed was not maintained, repairs, refurbishments, or replacements were done which had adverse financial and time consequences. Strict quality control is an important aspect for projects to ensure that the equipment received meets the correct standards and is fit for purpose. It also ensures that a person/contracting company is assigned the responsibility for equipment so that accountability is in place in the event that any issues arise.

3.6.2 Operational Challenges

- **Onsite Laboratory**: Routine sampling and testing for turbidity and free and total chlorine must be done every two hours by operators on site; however, the FERDP does not have a dedicated laboratory space. Laboratory equipment was utilised in the classroom located at the ATP building; however; it is recommended that a small laboratory space should be retro-fitted for testing purposes in the future.

- **Standby/Portable Monitoring Equipment**: Standby monitoring equipment or portable meters should always be availability in a case equipment repairs are needed. Due to the lack of a turbidity meter, the ATP system could not operate since turbidity measurements cannot be performed. In the event highly turbid water passes through the units, it could lead to failure of equipment, in particular the membranes and could adversely affect the water quality. In such a case, only the HP wash plant is operated to provide the main plant with process water. Visual checks still need to be done so as to not allow sludge-like effluent into the HP wash plant.

- **Pipe inlet to FERDP**: During Stage 3 Commissioning of the FERDP, the design flow rate of 2 ML/d was initially not achievable. Upon investigation it was found that there was an airlock in the pipe inlet which feeds final effluent from Darvill WWTW and this had to be flushed out to allow the flow to pass through easily.

- **Online sensors and the streaming current detector (SCD)**: the sensors that measure the turbidity and pH for the FERDP influent has a sieve that gets blocked every two hours due to the high suspended solids coming in. This causes no flow to the sensor and leads to inaccurate readings.

- **Clarifiers**: Algae build-up was observed in the lamella plates of the clarifiers. Algae can have adverse effects on rapid gravity sand filters, affecting the filtered water quality. Due to the exposure of the lamella plates to harsh weather conditions causing them to become brittle, pressure cleaning was not a viable option. As an interim solution, the clarifiers were soaked with high test hypochlorite (HTH) granules to remove the algae. A pre-chlorine dosing line was later installed in the final effluent chamber to reduce the algae build-up in the process. Clarifier covers were also installed after draining the clarifiers and cleaning with HTH to prevent algae growth. A contraption for the clarifier covers to be easily removed is still required so that the operators can visually observe the lamella plates. The clarified water turbidity improved thereafter. An additional recommendation would be to remove the clarifier plates completely to clean them and to include the use of HTH as a part of maintenance and cleaning.

- **Clarified water sampling**: the sampling point for the clarifiers are not effective since one is forced to sometimes sample from the channel itself which is not a true reflection of the clarified overflow water. The clarifier covers and position of the clarifier overflow weirs pose a challenge for sampling. A recommendation would be to get an appropriate sampling device that can reach the clarifier overflow weir so that an accurate sample can be obtained.

- **Rapid gravity sand filters**: During visual observation, uneven and erratic backwashing was noticed. There is a space between the floor of the trough and the filter media which causes the water to change route during backwashing resulting in uneven aeration and flow distribution.

- **GAC filters:** The GAC filters would overflow through the air relief valves installed at the top of the column which resulted in loss of GAC media. A pipe was installed to direct the water to a common manifold. The duty and standby feed pumps for the GAC filters were also leaking and the standby pump had a fault causing it to not operate. One of the challenges faced with the GAC filters was the delayed response time from contractors to fix the feed pumps; hence, the ATP had to operate by bypassing the GAC filters. Since the GAC units were offline for several weeks, biological growth was possible in the pipes and vessels hence the water in the filters must be drained, pipes need to be opened and flushed and the GAC media must be rinsed before operation can resume.

- **Ozone leaks:** There was an incident of an ozone leak during the early phases of commissioning due to the failure of the catalytic convertor on the generation unit. This had no effect on the production. At a later stage during commissioning, the catalytic converter failed again and required replacement. The installation of the new catalytic converter had to be done by the supplier’s technician who is not based in the KwaZulu-Natal province hence, this caused delays and ozone was not dosed for prolonged periods of time.

- **Ozone demister:** The ozone demister unit works by draining out the water to prevent it from entering the catalytic thermal destructor. However, draining of the demister was controlled manually by operators since the solenoid valve was not working. Draining of the demister was required every 10 to 15 minutes which posed a challenge for operators. Incidents occurred whereby water would fill the demister which reduces the amount of ozone that can be produced. The manual valve cannot be left open as this would result in an ozone leak. On one occasion, water entered the thermal destructor and reduced the effectiveness of the catalyst thereby causing an ozone leak. The solenoid valve was eventually replaced and commissioned to work automatically under level control.

- **Ozone dosing:** the flow from the ozone dosing point to the GAC only allows for a reaction time of two minutes before the next step which is insufficient. This was also a reason that precipitate manganese was found in the pipeline after GAC due to inadequate oxidation time. A tank was proposed to be installed to increase the reaction time.

- **Ozone process unit:** The ozone generation unit was not working optimally due to the compressor that required servicing. Once the compressor was serviced, the ozone unit was unable to generate any ozone even though it was operating. The ozone generation unit requires servicing in order for it to be put back online.

- **Prechlorination:** the prechlorination line was installed to address the algae issue that was affecting the clarifiers however, dosing was not accurate since there was preferential flow to the prechlorine and not post-chlorine line. Obtaining the correct ratio has been a trial and error process. It was proposed that a rotameter be installed to control the prechlorine dose and avoid the preferential flow.

- **Post-chlorination:** The post-chlorination operates when the ATP system is online but there is no post-chlorination line for the bypass. This often results in E.coli out of ranges on the final water sample when only the HP wash plant is operation.

- **Ultrafiltration feed pumps:** In a case where the ATP must be bypassed, the HP Wash plant will operate using the UF pumps to direct filtered water from the UF buffer tank to the final water tank. The UF feed pumps do not operate automatically when the plant is configured to run the HP Wash plant only. The pumps have to be set to local mode and started in the field. In addition, the manual valve to the UF skid must be closed and the manual bypass valve on the line feeding the final water tank must be opened. This poses a threat for pump cavitation if the control is not robust which is challenging when operating manually. It is therefore recommended that the SCADA control be updated to ensure that the HP Wash plant process with ATP bypass can operate automatically.

- **Ultrafiltration Membranes:** Membranes are required to be in stored in low concentration cleaning solution in the extended soak mode when not in use for more than 7 days to prevent biological growth. Shutdowns of the UF usually occur and sometimes for extended periods of time but the extended soak is not done. This could be detrimental for the lifecycle of the membrane in the long term.

- **Ultrafiltration Clean-in-Place (CIP):** CIP has primary and secondary wash stages. The secondary process utilises sulphuric acid and citric acid as cleaning solutions however, it was found that the citric acid pumps do not start when the process for chemical dosing is initiated during the CIP cycle. This suggests cleaning of the membranes may not be as effective as required since citric acid is a chelating agent for organo-metallic foulants to aid in their removal.

- **Configuration 2:** the HP-UF-PROMIX-GAC-FINAL configuration posed constraints due to GAC media being present in the final water hence, this configuration was not further tested during this period but will be further investigated at a later stage.

- **Response time to plant issues:** one of the challenges being faced is that systems such as the ozone and OSEC work well but when issues do arise due to required servicing or if there are faults after loadshedding, the response time to deal with such problems are delayed. Sometimes there is no timeline given for the servicing since the plant maintenance team do not have the adequate knowledge to do the repairs required or find the fault.

- **Loadshedding:** As mentioned previously under project challenges, loadshedding and power outages results in loss of production since the plant is offline for that period. Once power returns, it takes time for the plant to start-up again as well as for SCADA to connect to the server and flow to the FERDP to stabilise.

- **Water quality monitoring:** There were challenges with monitoring certain water quality parameters due to insufficient reagents required for tests such as the ozone ampoules required for ozone residual testing. There were also issues with procurement of certain chemicals which were attributed to external factors such as the Russia-Ukraine war which had an adverse impact on imports into South Africa.

- **Knowledge sharing:** There is a lack of communication and knowledge sharing between different contractors such as the electrical and instrumentation teams. The safety interlocks were not adequately communicated hence, when a repair had to be done, the electrical team could not find the fault immediately. This causes delays in operation and increases the downtime of processes. This issue also reiterates the need for a final approved FDS to be issued to all involved disciplines before the plant is in operation.

3.7 LESSONS AND CONSIDERATIONS

- Address all outstanding snags that were noted during commissioning and installation of the new modifications that were proposed such as the installation of an additional tank to increase contact time for ozone.
- An ozone demand investigation should be conducted.
- An in-depth analysis of the technology used on the FERDP will be conducted when all unit processes are in operation for both configurations over a stipulated period of time. This will have a project plan and defined outcomes that must be achieved.
- A jar test matrix should be done for different final effluent turbidities so that it can be used as a reference when required for chemical dosing.
- Process train 2 which is HP-UF-Promix-GAC-Final needs to be investigated for a set period of time to determine the efficiency of the system.
- A post-chlorination dosing line for the ATP-bypass system should be considered.
- A benchmarking exercise should be carried out at one of the large uMngeni-uThukela Water treatment works where all routine, periodic and specialised water analyses must be duplicated for comparison with the final water produced by the demonstration plant.

CHAPTER 4: DEVELOPMENT OF A WATER REUSE SAFETY PLAN

4.1 BACKGROUND

Water quality, security of supply, water treatment technology, costs, social and cultural perceptions and environmental considerations are key considerations that affect choices related to water reuse as an option. One of the major challenges when dealing with direct potable (DPR) plants is that one incident that could potentially compromise the community's health. If proven to originate from the plant, it will have a high probability of causing the plant's closure in extreme or significant financial losses due to lawsuits. Therefore, it is in the interest of the plant owner to ensure that good data are produced from a robust monitoring program (Swartz, et al., 2015). DPR plants have been installed in several countries worldwide; however, safe operational planning and governance of these processes are yet to be standardised globally and locally. This chapter outlines water reuse safety planning for the Darvill Final Effluent Reuse Demonstration Plant (FERDP) by following concepts established in the World Health Organisation's guidelines for water and sanitation safety plans as well as the recently published guideline for producing safe potable reuse water. This Darvill Water Reuse Safety Plan (WRSP) report focuses on assuring safe operation of the proposed water reuse treatment scheme to prevent detrimental health and environmental outcomes for the public, site personnel and potential end-users. It includes a comprehensive risk assessment matrix for all systems and sub-systems related to the FERDP. The demonstration plant will be used to investigate the reliability of the treated water supply and quality to national potable water standards; to provide valuable information on emerging contaminants of concern; to assess the overall lifecycle costs; to investigate the effectiveness and efficiency of different treatment configurations; to develop national water quality guidelines (regulation/limits) for potable water obtained from treated wastewater and to educate the public and improve perceptions of DPR plants as a potable water source. Therefore it is important that the WRSP must be developed and updated periodically, according to the findings from the various studies conducted.

4.2 ASSEMBLING THE TEAM

Stakeholders from different departments in UUW were identified, and a team was assembled. This team was responsible for guiding the development, implementation, continuous assessment and maintenance of the WRSP. The team should also ensure effective communication with external stakeholders. The team comprised of people with various skills, expertise and different professions including process engineers, scientists, laboratory staff, plant operators, maintenance workers, asset managers, technology installation contractors and researchers, thus bringing a unique set of skills and perspectives to the project. The success of the WRSP depends upon the members of the team.

4.3 SYSTEM BOUNDARIES

DPR schemes constitute a combination of different sub-systems which are closely connected and contribute different risk aspects. Therefore the boundaries of the system were defined in order to identify all relevant stakeholders that are to be involved in the development, implementation and maintenance of the WRSP (Hochstrat, et al., 2017). The FERDP was designed and constructed as an extension to Darvill WWTW; hence, any hydraulic and biological changes within the catchment area and the WWTW impact the downstream processes at the reuse plant. Table 4-1 shows a summary of the various subsystems that were considered for development of the Darvill WRSP.

Table 4-1: Subsystems considered for the Darvill WRSP

Name of Subsystem	Aspects to be considered in WRSP
Darvill WWTW Catchment	• Industrial/trade effluent discharges. • Inflow variabilities due to stormwater drainage, urban run-off.
Darvill WWTW	• Hydraulic/biological treatment capacity. • Seasonal variation of flow and demand.
Darvill FERDP	• Feed water quality, i.e. treated effluent from Darvill WWTW. • Product water quality. • Reliability of individual advanced treatment units.
Distribution & storage	• Water quality deterioration (regrowth). • Leakage or intrusion.
Reuse Water Application	• Water quality and safety of site personnel (for use as service water on Darvill WWTW). • Local community (public perception).

4.3.1 Darvill WWTW Catchment:

Darvill WWTW is the largest and most significant wastewater treatment plant under uMngeni-uThukela water's (UUW) management, and serves the Msunduzi Local Municipality (refer to Figure 4-1). Increased rainfall during the summer months leads to the ingress of stormwater into the sewer system, resulting in an exceedance of the hydraulic capacity of the plant. The plant has been upgraded to 120 ML/d in order to cope with the following:

- Additional inflows received as water consumption in the WWTW supply area;
- Addition of new supply areas; and
- Higher flows during wet seasons.

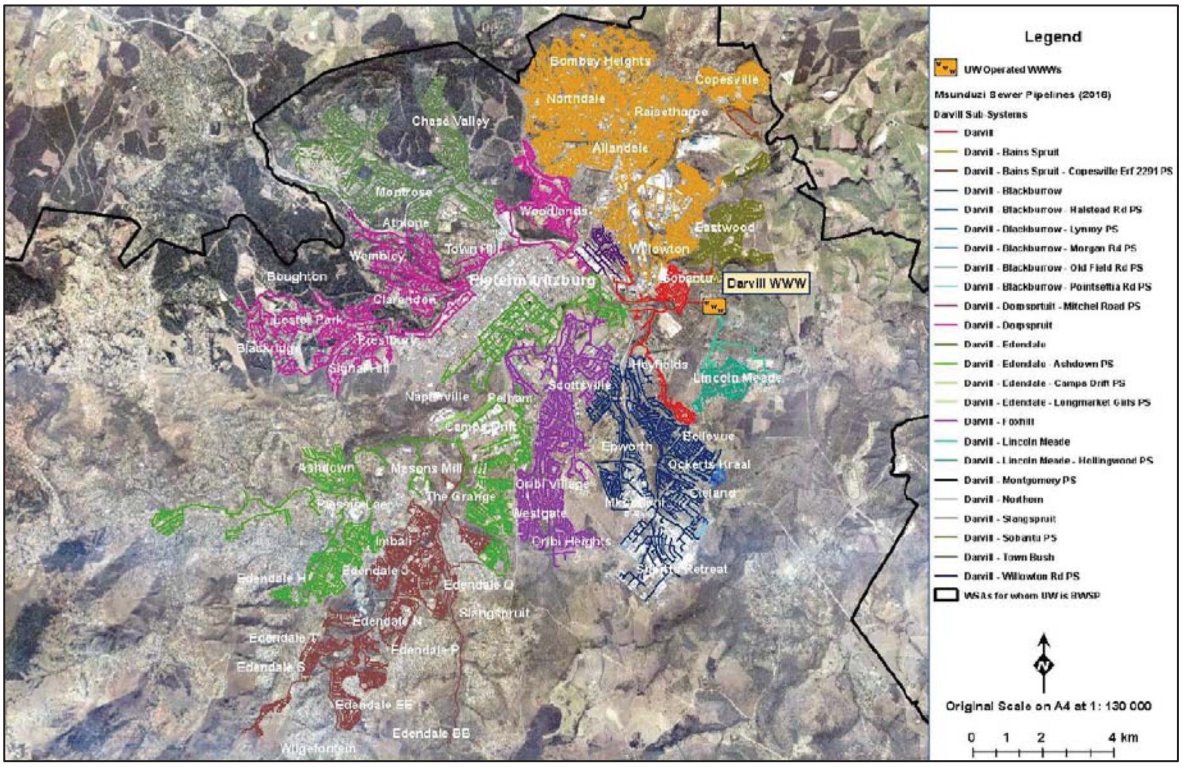

Figure 4-1: Location of Darvill WWTW in relation to the collection system (Umgeni Water, 2021)

4.3.2 Trade Effluent Management:

The Msunduzi Municipality appointed uMngeni-uThukela Water to manage trade effluent discharge by industries within the Darvill WWTW catchment. Similar to any municipal wastewater treatment works, Darvill WWTW is designed to handle predetermined organic, nutrient and hydraulic loads. Overloading the plant often results in poor process performance leading to non-compliance and thus environmental pollution. Domestic effluent can be predictable in terms of expected load and volumes. Industrial/trade effluent quality, however, often varies wildly depending on the production stage and processes used by a particular industry. Some trade effluents contain chemical compounds which are either inhibitory to wastewater treatment processes or cannot be treated by conventional means. Wastewater treatment works treating both domestic and trade effluent is thus more prone to non-compliance.

To mitigate the risk of trade effluent discharge-related non-compliance, Msunduzi Municipality has limits on the quality of industrial effluent to be discharged to Darvill WWTW as laid out in the bylaws. The bylaws specify the allowed limit for each monitored parameter, and surpassing these criteria leads to wastewater works discharging non-compliant effluent into the environment. uMngeni-uThukela water (UUW) conducts sampling of industries at a minimum frequency of once a month depending on the nature and the toxicity of the effluent produced. Trade effluent assessments are done twice a year. This is where uMngeni-uThukela Water personnel use the average monitored chemical oxygen demand strength over six months, together with the volume discharged to bill each industry. A trade effluent charge is then forwarded to the Municipality to be included in the industry's utility bill (Mnguni & Mazibuko, 2019).
Wastewater Risk Abatement Plan:

The Department of Water and Sanitation (DWS), as the national custodian of South Africa's water resources and the overall leader of the water sector, is responsible for the regulation of water services. The Green Drop System is a regulatory tool used by DWS to monitor, manage, and reduce the risks associated with wastewater treatment and discharge. The Green Drop process measures and compares the results of the performance of Water Service Authorities and the respective Water Service Providers, and subsequently rewards (or penalises) the municipalities on evidence of their excellence (or failures) according to the minimum standards or requirements that has been defined. Green Drop certification is awarded to Water Services Institutions that comply with 90% of the criteria set by DWS for wastewater management. One such requirement is the development of Municipal Wastewater Risk Abatement Plans (WRAPs). The WRAP encompasses all steps in the wastewater value chain from production to discharge or reuse in a particular catchment. The development of the WRAP draws on many of the principles and concepts from other risk management approach in particular, the Water Safety Plan (WSP), Hazard Operability Study (HAZOP) and Hazard Analysis & Critical Control Points (HACCP) (Umgeni Water & Msunduzi Municipality, 2021).

A WRAP has three key components which are guided by health-based targets and overseen through surveillance of effluent released by wastewater treatment works (Umgeni Water & Msunduzi Municipality, 2021). These are:

- System assessment to determine whether the wastewater treatment as a whole can deliver effluent of a quality that meets health-based and environmental targets. This also includes the assessment of design criteria of new systems;
- Identifying control measures in a wastewater treatment system that will collectively control identified risks and ensure that the health-based and environmental targets are met. For each control measure identified, an appropriate means of operational monitoring should be defined that will ensure that any deviation from required performance is detected on time; and
- Management plans describe actions to be taken during normal operation or incident conditions and document the system assessment (including upgrade and improvement), monitoring and communication plans and supporting programs.

uMngeni-uThukela water and Msunduzi Municipality develop the WRAP for Darvill WWTW on an annual basis. The outcomes of the report include a semi-quantitative risk assessment, with a scope that covers all hazardous activities within the catchment, trade effluent monitoring and the individual treatment processes for Darvill WWTW.

4.4 SYSTEM ASSESSMENT

4.4.1 System Description

A detailed description of the catchment system and biological treatment processes for Darvill WWTW is provided in the annual Darvill Wastewater Risk Abatement Plan (Umgeni Water & Msunduzi Municipality, 2021). Figure 4-2 shows the process flow diagram of the Darvill FERDP. The unit processes are described in details in Section 2.2.

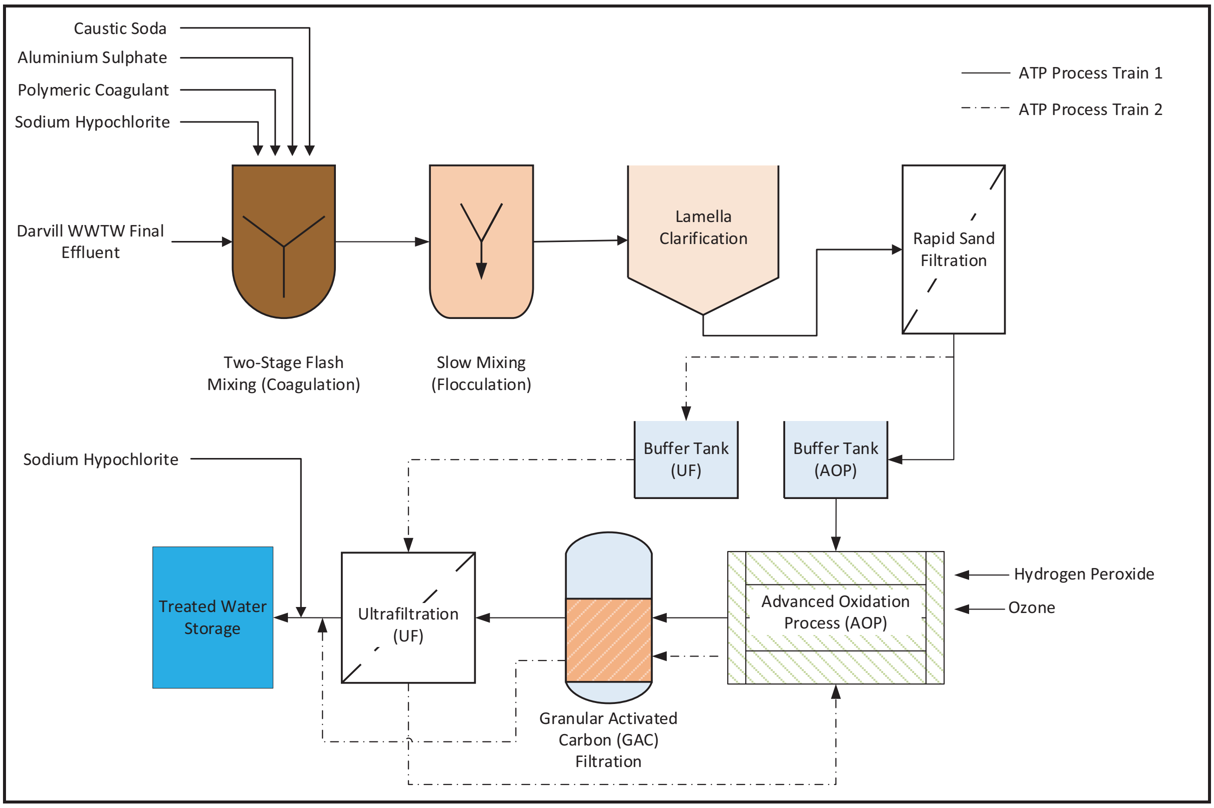

Figure 4-2: Process Flow Diagram of the Darvill Final Effluent Reuse Demonstration Plant.

4.4.2 Hazard Analysis and Critical Control Points

For this report, the water reuse safety plan largely focused on the hazards and risks that arise from operations and management of the Darvill FERDP. Major influencing hazards and risks from catchment activities and Darvill WWTW were extracted from the Darvill Wastewater Risk Abatement Plan (WRAP) report for the period 2020/2021. The first draft of the WRSP was prepared using the uMngeni-uThukela Water water/wastewater risk assessment template which was developed by the Water and Environmental Services department within the Scientific Services division. Adaptations were made to the risk assessment template to incorporate the hazard analysis and critical control point (HACCP) approach by Halliwell et al. (2014). The HACCP approach is based on seven principles that allow for the detection and correction of process deviations at the earliest possible opportunity, as illustrated in Figure 4-3 below.

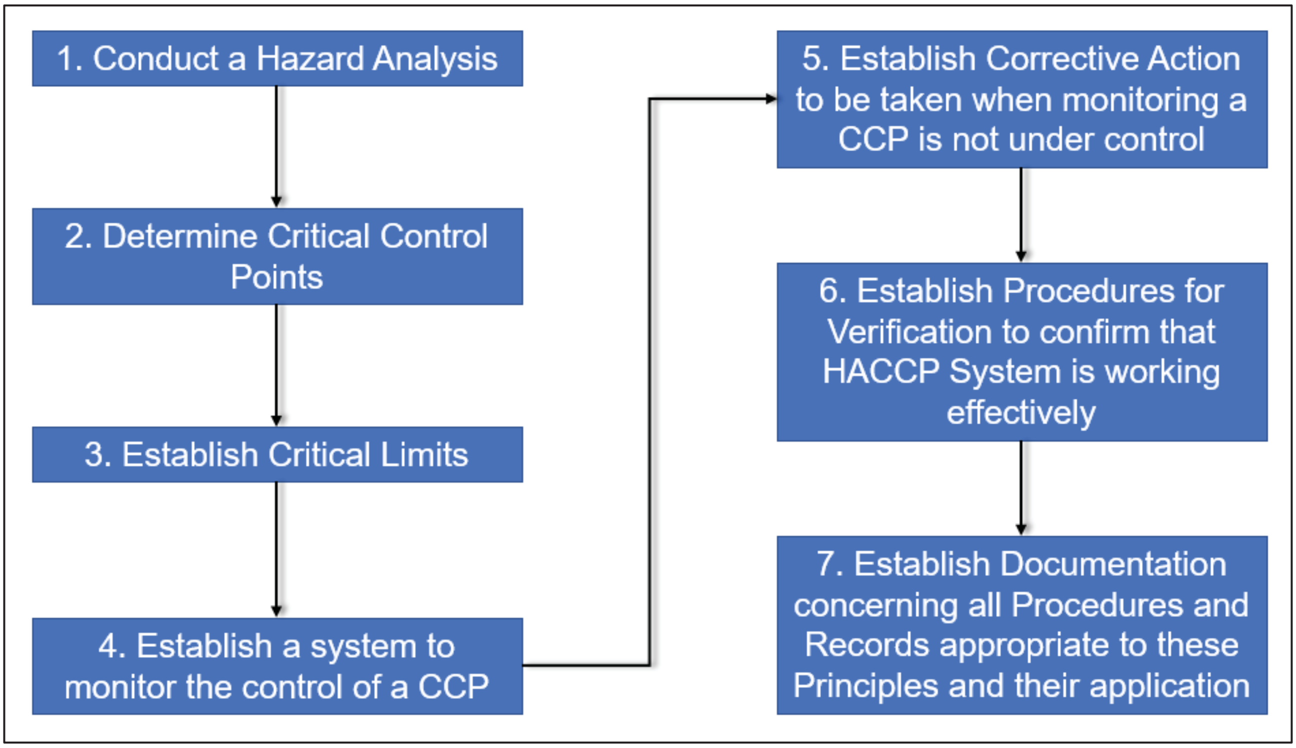

Figure 4-3: Flow diagram of the HACCP approach

4.4.3 Identify Hazards and Hazardous Events

Identifying potential hazards and work risks is expected to facilitate the company in the management and control of safety in the workplace and minimize the possibility of accidents. A hazard is a biological, chemical, physical, or radiological agent that has the potential to cause harm such as human injury or ill health and/or damage to property and the environment. A hazardous event is an incident or situation that can lead to the presence of a hazard (van der Merwe-Botha & Manus, 2011). The hazard identification process involved the identification of undesired events that can lead to the hazard occurring. Hazards can be designated into three categories; health, safety, or environmental hazard. An occupational health hazard can cause illness to an individual, and these effects can be acute or chronic. A safety hazard can cause injury to a person or damage to property/equipment. An environmental hazard is a release that has detrimental effects on the environment.

The following documentation can be used for the process of hazard identification:

- First aid and injury records;
- Investigation reports on previous hazardous events;
- Workplace inspection reports;
- Record of hazardous substances and Material Safety Data Sheets

The study was initiated using the HIRA (Hazard Identification and Risk Assessment) method to identify all existing and potential hazards for the Darvill FERDP. Each process step in the conventional and advanced treatment sections of the FERDP was analysed. Data was collected through observation and surveillance during commissioning on site, interviews of site personnel and contractors, literature review and hazard/risk studies for similar processes.

4.4.4 Describe & Assess Control Measures

Once the hazards have been identified, an assessment of the level of risk was conducted for each hazard. Risk is the likelihood of identified hazards causing harm in exposed populations in a specified time frame, including the magnitude of that harm and/or the consequences (van der Merwe-Botha & Manus, 2011). Not every hazard will require the same degree of attention, hence the risks associated with each hazard or hazardous event was compared to ensure that priorities for risk management can be established and documented. The type of risks includes the impact on public health and the environment, aesthetic effects and continuity of processes and adequacy of supplies.

Control is the elimination or inactivation of a hazard in a manner such that the hazard does not pose a risk to workers who have to enter into an area or work on equipment in the course of scheduled work (Department of Occupational Safety and Health, 2008). Hazards can be controlled at the source, between the source and the worker or at the level of the worker. Selection of suitable control measures involves evaluating, selecting and implementing short and long term control measures.

Various control measures can be applied to manage hazards effectively within the workplace. These measures encompass a range of strategies, including hazard source intervention, engineering controls, and administrative safeguards. At the source of the hazard, one approach involves the elimination of the hazard or its substitution with a less perilous alternative. Engineering controls comprise methods such as redesigning processes, implementing isolation measures, automation, the use of barriers, as well as mechanisms for hazard elimination, absorption, or dilution. Additionally, administrative controls play a crucial role in ensuring safety and include the establishment of secure work procedures, ongoing supervision and training, job rotations to reduce exposure to hazards, effective housekeeping practices, robust repair and maintenance programs, and rigorous hygiene protocols.

The combination of these control measures collectively were taken into account to provide a safer work environment and hazard mitigation. Additionally, the effectiveness of the above mentioned control measures are monitored and evaluated regularly to determine if the problems are solved, the introduction of new hazards are being controlled, analysis of incident reports and re-evaluate hazards and apply new control measures if required. The effectiveness of the control measures in place for all hazards identified for the Darvill FERDP system was determined using percentage ratings as stipulated in uMngeni-uThukela water's Integrated Risk Management Framework Procedures Manual (Table 4-2).

Table 4-2: uMngeni-uThukela Water's Integrated Risk Management Framework Procedures Manual

CONTROL EFFECTIVENESS		
Percentage	Outcome Description	Level
95-100%	Responses are preventative, are in place and substantially reduce the probability of occurrence	Excellent
90-94.9%	Responses and detection mechanisms are in place, effective and partially reduce the probability of occurrence	Very good
70-89.9%	Responses and detection mechanisms are in place and are pro-active in nature	Good
50-69.9%	Responses are in place and effective but are mostly reactive in nature	Reasonable
30-49.9%	Management and physical responses are in place but not maintained, appropriate or effective	Poor
0-29.9%	No responses are in place or the majority of controls have failed in the last 10 years	Unsatisfactory

4.4.5 Assess & Prioritise Risks

The hazard identification process yields an extensive list of hazards and hazardous events, which pose minimal, moderate or significant risks. A semi-quantitative matrix is utilised to distinguish between these risks by taking into consideration the likelihood of occurrence (e.g. certain, possible, rare) and evaluating the potential severity of consequences (e.g. insignificant, major, catastrophic) linked to each hazard or hazardous event. This methodology is aligned with the guidance provided by van der Merwe-Botha & Manus, 2011. The likelihood is determined by "how often' or "how likely" a hazard or a hazardous event occurs and it takes into account hazards that have occurred in the past and the likelihood of re-occurrence into account. The Severity/Consequence was used to assesses both the severity of the results of the hazard/hazardous event and the degree of intensity in its impact.

In the course of the implementation of the semi-quantitative matrix risk assessment, scores for likelihood and severity was assigned to each identified hazardous event to derive an overall risk score category (e.g. very high, high, medium, or low). This likelihood was determined using the guideline provided by Falakh & Setiani (2018), as shown in Table 4-3.

Table 4-3: Hazard likelihood, frequency and severity level (Falakh & Setiani, 2018)

Score	Likelihood/ frequency	Expected or actual frequency experienced	Severity Level
1	Rare	May only occur in exceptional circumstances; simple process; no previous incidence of noncompliance.	• Minor onsite injuries (first aid and nondisabling, reportable injuries). • Property damage less than base level amount. • Minor environmental impact (no remediation required). • Loss of production less than base level amount. • No offsite impact or damage. No public concern or media interest.
2	Unlikely	Could occur at some time; less than 25% chance of occurring; non-complex process and/or existence of checks and balances.	• Serious onsite injuries (temporary disabling worker injuries). • Property damage from 1 to 20 times base level. • Moderate environmental impact (cleanup or remediation in less than 1 week and no lasting impact on food chain, terrestrial or aquatic life). • Loss of production from 1 to 20 times base level. • Minor offsite impact (public nuisance – noise, smoke, odour, traffic). • Potential adverse public reaction. Some media awareness.
3	Possible	Might occur at some time; 25-50% chance of occurring; previous audits/reports indicate non-compliance; complex process with extensive checks & balances; impacting factors	• Permanent disabling onsite injuries or possible fatality. • Property damage from 20 to 50 times base level. Significant environmental impact (cleanup or remediation less than 1 month and minor impact on food chain, terrestrial or aquatic life). • Loss of production from 20 to 50 times base level. • Moderate offsite impact limited to property damage, minor health effects to the public or first aid injuries. • Adverse public reaction. Local media concern.

Score	Likelihood/ frequency	Expected or actual frequency experienced	Severity Level
		outside control of organisation.	
4	Likely	Will probably occur in most circumstances; 50-75% chance of occurring; complex process with some checks & balances; impacting factors outside control of organisation.	• Onsite fatality or less than four permanent disabling worker injuries. • Property damage from 50 to 200 times base level. • Serious environmental impact (cleanup or remediation requires 3 to 6 months and moderate impact on food chain, terrestrial and/or aquatic life). • Loss of production from 50 to 200 times base level. • Significant offsite impact property damage, short-term health effects to the public or temporary disabling injuries. • Significant public concern or reaction. National media concern.
5	Almost certain	Can be expected to occur in most circumstances; more than 75% chance of occurring; complex process with minimal checks & balances; impacting factors outside control of organisation.	• Multiple onsite fatalities or four or more permanent disabling onsite injuries. • Property damage greater than 200 times base level. • Extensive environmental impact (cleanup or remediation exceeding 6 months, significant loss of terrestrial and aquatic life or damage to food chain uncertain). • Loss of production greater than 200 times base level. • Severe offsite impact property damage, offsite fatality, long-term health effect, or disabling injuries. • Severe adverse public reaction threatening facility continued operations. International media concern.

4.4.5.1 Inherent Risk:

'Inherent risk' refers to the natural risk level of a hazard that has not been controlled or mitigated. The inherent risk score for each hazard identified for the Darvill FERDP was determined using equation 4-1 below:

$$Inherent\ Risk = Severity * Frequency \qquad (4\text{-}1)$$

4.4.5.2 Residual Risk:

Residual risk takes into consideration the control effectiveness of any measures or responses in place to mitigate hazards in a process. Residual risk score was calculated using equation 4-2:

$$Residual\ Risk = Inherent\ Risk - (Inherent\ Risk * Control\ Effectiveness) \qquad (4\text{-}2)$$

4.4.5.3 Risk Rating:

'Risk rating' refers to the classification of residual risks. Method of classification will vary across different processes and organisations. All risks for the Darvill FERDP were rated based on the same classification method used in the risk assessment for the Darvill WRAP (see Table 4-4 below).

All risks will be addressed through improvement actions; however, priority will be given to risks that are rated as 'high' and 'very high'.

Table 4-4: Classification of Risks

Risk score	< 6	6-9	10-15	>15
Risk rating	Low	Medium	High	Very High

4.4.6 Identify Critical Control Points

Critical control points (CCPs) in drinking water management systems refers to an activity, procedure or process that is critical to control to reduce or eliminate a particular water quality hazard. These control points must be monitored consistently to ensure the effectiveness of each step in the process of the treatment train. The most important CCPs identified for conventional water treatment processes are filtration, disinfection and storage of final water. Halliwell et al. (2014) developed a five-question metric, commonly referred to as the HACCP 'Decision Tree', for identifying (CCPs) in water reuse systems. Walker et al. (2016) modified one of the questions to be specific to a potable reuse scenario, in which the potential hazards are specifically phrased in terms of pathogen log reduction and water quality targets (Figure 4-4). The abovementioned decision tree analysis will be applied for all hazards identified in the risk assessment for the FERDP.

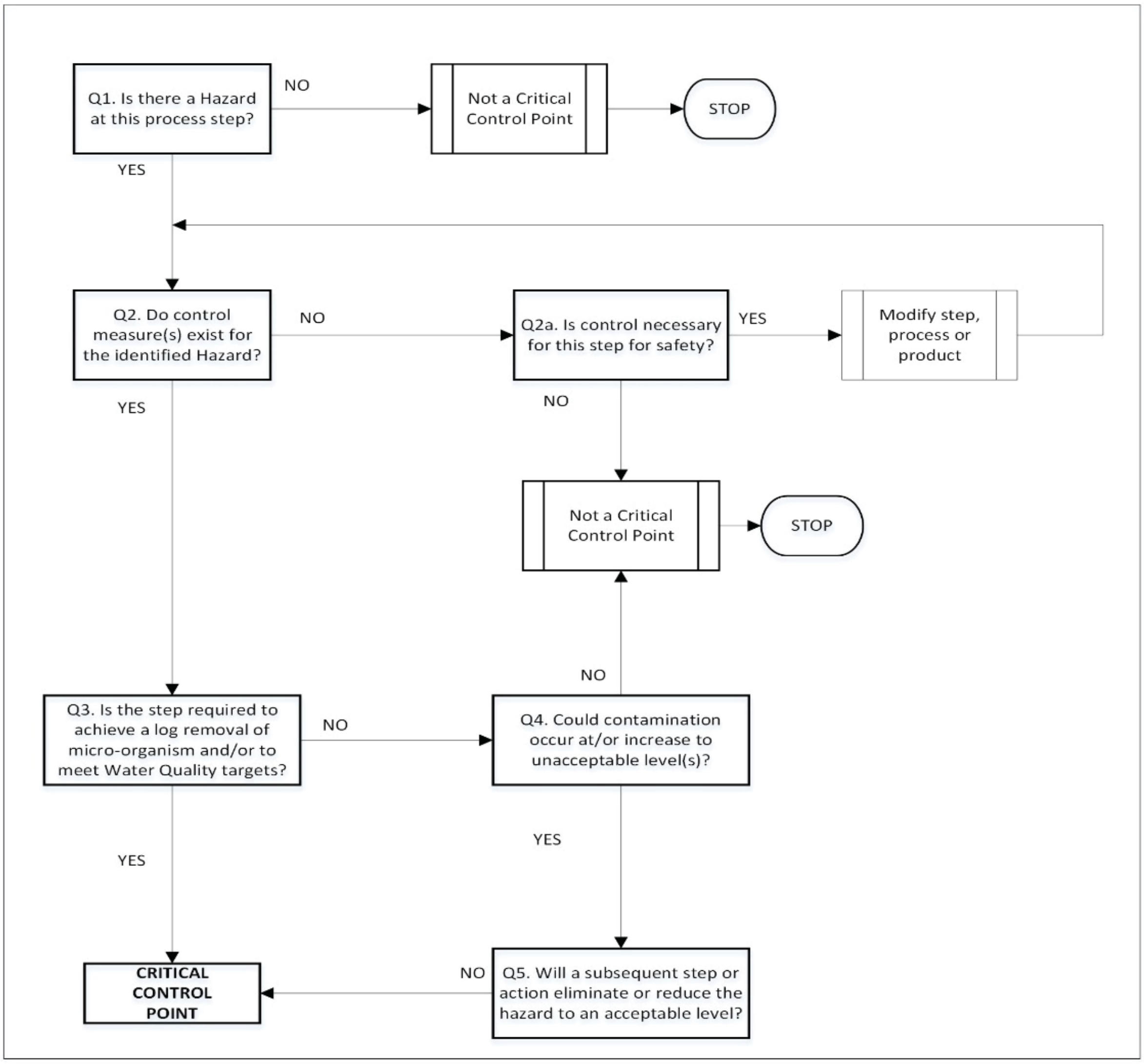

Figure 4-4: HACCP 'Decision Tree', for identifying (CCPs) in water reuse systems (Walker, et al., 2016)

4.4.7 Establish Critical Limits

The crucial step of establishing critical limits is undertaken to identify the acceptable range of values for various parameters, including physical, chemical and microbial aspects. These limits were defined in accordance with SANS 241: 2015 quality parameters to ensure the safety and effectiveness of the DPR plant treatment process.

4.5 OPERATIONAL MONITORING

It is one of the key characteristics of risk management approaches not only to confirm the water quality as a result of water treatment but also to monitor the process itself. The monitoring system has three key components at the FERDP; effluent monitoring, operational and control monitoring, and compliance monitoring. This monitoring system enables early detection of the incoming effluent quality (rapid changes in the effluent quality), maintenance of treatment barriers in the plant through setting operational alert levels for the various unit operations and compliance of the final potable water quality with respect to the South African National Standards (SANS 241: 2015) as well as preliminary proposed water quality targets stated in WRC Report No. TT 882/22 *"A Water Reclamation and Reuse Guide for South African Municipal Engineers"* (Swartz, et al., 2022) .

4.5.1 Monitoring Programme

Although measuring parameters at control points is a standard way of monitoring, observational monitoring might be useful, particularly where suitable analytical capabilities are missing. Audits and visual inspections using checklists and interviews can be beneficial as well and help operators to better understand the functionality of the system as well as the background of the risk management process. While establishing monitoring parameters and water quality limits, methods, frequency and responsibility are crucial to consider. The frequency of monitoring needs to be defined to enable rapid response if notable deviations occur which affects final water quality or other products.

In water reuse systems, starting at the wastewater system is particularly important due to high variabilities and high level of microbial and chemical hazards. Parameters and methods detecting unauthorised industrial discharge and high variability during extreme meteorological events in the wastewater collection system might be advisable. Fast response times between the sample, measurement and the alarm are important especially in potable reuse schemes in order to detect a failure or trend leading to a failure before water is supplied to the customer. In such cases, online monitoring systems and real time data reporting are advisable. Grab samples and more complex analyses can validate online monitoring tools.

Quality standards and guidelines have been developed for monitoring minimum standards for potable water use and discharges into water resources from wastewater treatment processes and industries (NWRS II, 2013):

- South African National Standard (SANS) 241: 2015 for drinking water
- South African Water Quality Guidelines for a number of different water user sectors (DWAF, 1996)
- General and Special Standards pertaining to the discharge of treated wastewater to the water resource

New regulatory and guiding documents will need to be developed by the Department of Water and Sanitation for water reuse. This may include aspects on water quality variables of concern, quantification of risks and acceptable risk levels and monitoring requirements in terms of frequency and location of sampling, etc. (NWRS II, 2013). Additionally, laboratory equipment and resources needed for monitoring must also be considered at this stage.

4.5.2 Water Quality Monitoring Plan

Water quality monitoring is important for ensuring that water is safe for public consumption and the results also provides information for decision making by management such as identifying actual and emerging problems of water pollution, formulating plans and setting priorities for water quality management, developing and implementing water quality management programmes and evaluating the effectiveness of management actions (Behmel, et al., 2016) . The water quality monitoring plan should include the water quality parameters that are to be tested and the potential impact, sampling procedures, calibrations, frequency of tests and reporting and where the tests will be conducted, i.e. the plant laboratory or outsourcing. The plan should clearly state the sampling points and locations, contingencies and Incident Management Protocol (IMP) to be followed should there be an out-of-range result during onsite monitoring (EPA, 2020). Section 5.4.3 that follows provides further details on the water quality monitoring plan developed for testing microbial and chemical parameters at the Darvill FERDP.

4.5.3 Microbial & Chemical Water Quality Analysis

With regard to public health protection, microbial water quality analysis is essential and microbial water quality parameters should not exceed limits at all times. Microbial performance indicators such as *E.coli* and total coliforms are typical parameters to monitor water quality. For chemical water quality, the choice of parameters depends on the regulations, water source and inputs (regulated and unregulated) which can affect it, type of chemicals and processes used in the treatment processes as well as availability of analytical equipment and expertise. Key sampling points were identified at the Darvill FERDP as listed in Table 4-5. Figure 4-5 illustrates the specific locations of the key sampling unauthorized points for at the Darvill FERDP.

Table 4-5: Description of Sampling Points for Darvill FERDP

Sample Point No.	Description	Note for Sampling
1	Final (unchlorinated) effluent from Darvill WWTP.	Sample to be taken just after bend in channel to ensure well mixed sample.
2	Clarified water from lamella clarifiers (x 2).	Sample to be taken for exit of each clarifier OR combined sample.
3	Filtered water from rapid gravity filters (RGF) (x 3).	Each filter has its own sample tap located prior to buffer tanks for PROMIX and UF; hence, will be true representation of filtered water quality (i.e. no residence time in buffer tanks/cross contamination).
4	Feed to Pro3mix unit	Sample taken at the feed pump for Pro3mix unit.
5	Feed to GAC filters	Sample can be taken on discharge line of Pro3mix unit OR take from sampling points for GAC feed pumps.
6	GAC filtrate	Sampling point available for combined GAC filtrate; sampling points also available on exit lines of each GAC filter.
7	Feed to UF system	Sample taken at the feed pump for UF unit.
8	UF filtrate	Sampling point located on outlet line of UF unit.
9	Chlorinated final water (prior to storage tank)	Sampling point located next to storage tank for final water.
10	Final water (from storage tank)	Sampling point located next to storage tank for final water.

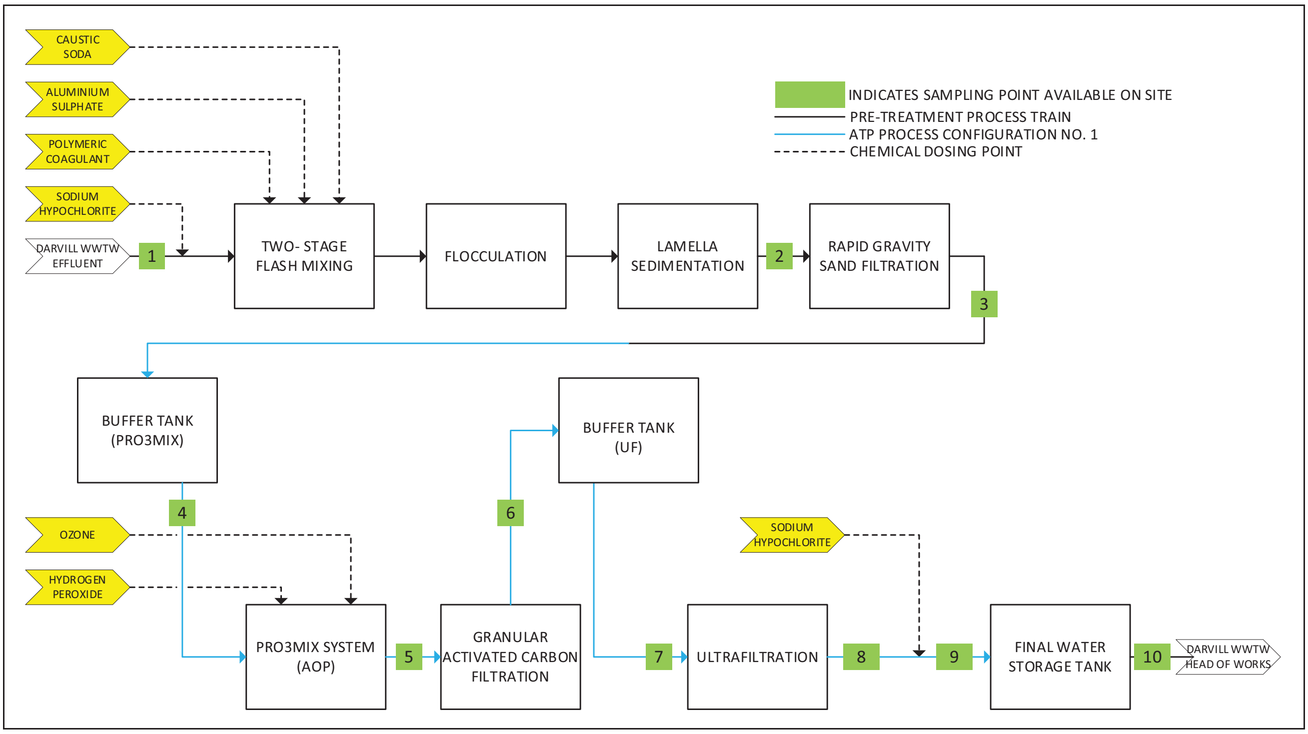

Figure 4-5: Block Flow Diagram for Darvill FERDP indicating water sampling points

During the operational and performance testing phase (refer to Chapter 6 for results), water quality parameters that were tested onsite were constrained according to the equipment available for testing. Sampling for turbidity and free chlorine concentrations was scheduled at two hour intervals as is standard practice for water treatment plants at uMngeni-uThukela water.

The flow rates and pressures for the ultrafiltration unit was recorded as well as the ozone dosage and residual ozone concentration were important parameters to note. Chemical dosages are important as the dose during a specific period can be correlated with the turbidity results and changes can be implemented if a need arises. Figure 4-6 shows an example of the log sheet utilised for routine daily monitoring at the FERDP.

The samples will be analysed by uMngeni-uThukela water Laboratory Services. The department is advised on the sample requirements in advance to ensure that the laboratory is fully resourced to support the required turnaround-times for analyses. Table 4-6 is the recommended monitoring programme developed for microbial and chemical water quality analyses at the Darvill FERDP.

Date: ____________ Operator 1: ____________

DAY SHIFT Operator 2: ____________

Configuration: ____________

Sampling Point	Parameters/ Units	Time					
		07:00	09:00	11:00	13:00	15:00	17:00
Final Effluent	m^3						
	m^3/h						
	NTU						
	pH						
Comb Clarifier	NTU						
	pH						
Filter 1	NTU						
	pH						
Filter 2	NTU						
	pH						
Filter 3	NTU						
	pH						
Ozone	mg/l						
	gO_3/h						
Promix Outlet	mg O_3/L						
GAC Feed	NTU						
GAC Product	NTU						
UF Feed	m^3/h						
	NTU						
	pH						
UF (PIT501)	kPa						
UF TMP	kPa						
UF Product	m^3/h						
	NTU						
	pH						
UF (PIT502)	kPa						
Final Water	m^3						
	NTU						
	pH						
	Cl (F)						
	Cl (T)						

Chemical Dosage	SCADA mg/l	FIELD mg/l
Polymer U3500		
Aluminium Sulphate		
Hydrogen peroxide		
OSEC		

AQC Results	Turbidity Meter		pH Meter			

Figure 4-6: Log sheet for onsite water quality monitoring at the FERDP

Table 4-6: Recommended Monitoring Programme for Microbial & Chemical Water Quality Analysis

Determinand	Frequency	No. of Samples (Annual Basis)	Sampling Points
Full SANS 241: 2015 Analysis	Fortnightly	26	1; 3; 4; 5; 6; 7; 8; 9
E.coli	Daily	366	1; 7; 9
Total coliforms	Daily	366	1; 9
Coliphages	Daily	366	1; 9
Vibrio cholerae	Weekly	52	1; 9
Salmonella	Weekly	52	1; 9
Clostridium perfringens	Daily	366	1; 7: 9
Trihalomethanes (THMs)	Weekly	52	5; 6; 9
Total organic carbon	Daily	366	1; 5; 6; 7; 8; 9
Geosmin and 2-MIB	Monthly	12	1; 9
Soluble organic carbon	Weekly	52	4; 5; 6
Aluminium	Daily	366	1; 3; 5; 6; 9
Iron	Daily	366	1; 3; 5; 6; 9
Manganese	Daily	366	1; 3; 5; 6; 9
Total suspended solids	Daily	366	1; 7; 9
pH	Daily	366	1; 9

Determinand	Frequency	No. of Samples (Annual Basis)	Sampling Points
Turbidity	Daily	366	1; 3; 6; 7; 9
Nitrates	Daily	366	1; 3; 5; 6; 9
Ammonia	Daily	366	1; 3; 5; 6; 9
Cryptosporidium	Weekly	52	1; 9
Giardia	Weekly	52	1; 9
Alkalinity	Daily	366	1; 9
Calcium	Daily	366	1; 9
Chemical oxygen demand	Daily	366	1; 4; 5; 7; 9
Conductivity	Daily	366	1; 9
Free chlorine	Daily	366	1; 2; 9
Total chlorine	Daily	366	1; 2; 9

4.5.4 Non-targeted Chemical Analysis

Non-targeted chemical analysis is recommended as it allows a more comprehensive understanding of the specific characteristics of the source water at the site and the performance of treatment steps. It is a proactive approach to identify potential risks and to ensure the safety of the water.

4.5.5 Monitoring Contaminants of Emerging Concern (CECs)

Emerging contaminants, which are not yet regulated, need to be assessed as well. However, regular and frequent monitoring for every potential chemical substance is not feasible. Chemical indicators are substances which are likely to be found in water and are representative for a class of chemicals and can be used for assessment of performance of processes. Surrogate parameters such as total organic carbon, volatile organic carbon and elemental carbon, are suitable and can be used for online monitoring of process performance as well. The previous WRC reports (No. T611/14 and No.1894/1/14) by Metcalf et al. (2014) were reviewed and a list of emerging contaminants and removal efficiencies as per literature from each unit process were sourced from these reports for inclusion in the draft WRSP. The spreadsheet developed for the WRSP (Table 4-9) was used as an input into the monitoring programme for the plant.

A list of CECs has been selected, taking into consideration their prevalence in South Africa's potable water and wastewater streams. Specific emphasis has been laid on chemicals that are distinctly predominant in the region, such as Antiretrovirals (ARVs) and Antibiotics. The selection was further refined based on recommendations of priority CECs for direct potable use (Swartz et al. 2018), and included chemicals representative of diverse groups. Additionally, the availability of analytical capabilities to detect and quantify these CECs was a decisive factor in the selection. Consequently, for the purpose of this study, a comprehensive array of 28 compounds that belong to nine pharmaceutical groups (including ARVs drugs, Antibiotics, Antidepressants, Antihistamines, Antihypertensive, Statins, Anti-inflammatory anticonvulsants, Benzodiazepines) has been selected (Table 4-7). These compounds predominantly encompass a broad spectrum of pharmaceutical constituents, chosen in adherence to the aforementioned criteria.

Table 4-7: Targeted contaminants of emerging concern

Pharmaceutical Category	Pharmaceutical	Functional Group	Hydrophilic Property
Antiretroviral drugs (HIV treatment):	Darunavir	Peptidomimetic	Moderate
	Nevirapine	Dipyridodiazepinone	Low
	Raltegravir	Oxadiazole	High
	Ritonavir	Peptidomimetic	Moderate
Antibiotics:	Clarithromycin	Macrolide	Moderate
	Erythromycin	Macrolide	Moderate
	Linezolid	Oxazolidinone	High
	Metronidazole	Nitroimidazole	High
	Piperacillin	Penicillin	High
Antidepressants:	Amitriptyline	Tricyclic	Low
	Citalopram	Selective Serotonin Reuptake Inhibitor	High
Antihistamines:	Antazoline	Ethylenediamine	Moderate
	Fexofenadine	Piperidine	High
Antihypertensive/Cardiovascular drugs:	Atenolol	Beta blocker	High
	Bisoprolol	Beta blocker	Moderate
	Carvedilol	Beta blocker	Low
	Eprosartan	Angiotensin II receptor antagonist	High
	Ibersartan	Angiotensin II receptor antagonist	High
	Metoprolol	Beta blocker	Moderate
	Telmisartan	Angiotensin II receptor antagonist	Moderate
Statins (cholesterol-lowering drugs):	Rosuvastatin	Statin	Low
Anti-inflammatory/analgesic drugs:	Diclofenac	Nonsteroidal Anti-inflammatory Drug (NSAID)	Low
Anticonvulsants:	Carbamazepine	Iminostilbene	Low
Benzodiazepines (anxiety/sleep disorder treatment):	Alprazolam	Benzodiazepine	Low
	Lorazepam	Benzodiazepine	Low
	Oxazepam	Benzodiazepine	Low
	Zolpidem	Imidazopyridine	Low

4.5.6 Monitoring of Performance of Treatment Steps

Methods used for monitoring of performance of treatment steps, such as integrity tests in membrane filtration or disinfection by-product control for chlorination need to be considered for each step. Whilst the plant was still in the performance testing stage, the effectiveness of the treatment technology installed at the Darvill FERDP were assessed intermittently. This aspect is discussed in Chapter 5.

4.6 VERIFICATION OF SYSTEM PERFORMANCE

The actions required when critical limits exceed the norm, as well as the responsible persons, need to be clearly defined. Verification of the system performance is intended to be done periodically to ensure that trends in overall system performance are detected. The verification of system performance can be done by monitoring the treated water quality, process control system, testing the performance of specific technologies (ultrafiltration, advanced oxidation process, GAC units or disinfection via OSEC) to verify the overall effectiveness of the Darvill FERDP.

4.7 MANAGEMENT AND COMMUNICATION

According to the World Health Organization’s Guideline for Drinking-water Quality (2017) effective management involves "setting priorities, allocating resources, and monitoring and evaluating performance". This involves setting clear objectives, establishing roles and responsibilities, providing resources and support, and implementing a system for ongoing monitoring and review. Effective management ensures that the plan is being implemented as intended and that any issues or concerns are identified and addressed in a timely manner. It is critical for protecting public health, minimizing financial losses, and ensuring compliance with regulatory requirements. All relevant documents containing detailed information regarding the operation of the treatment system were prepared. Control measures are recorded on HAZOP reports and response plans which are part of the O&M manual needs to be finalised. Sampling and monitoring plans were prepared. All documentation is stored as electronic copies within the UUW network which can be conveniently accessed by operators on their computers as recommended by WHO (Bartram J, et al., 2023). Hard copies of the O&Ms and SOPs will also available at the DPR plant. Table 4-8 shows examples of the available plant operation documentation.

Clear communication channels were established to ensure that all stakeholders are aware of the potential risks, measures taken and to provide feedback and input. By implementing these best practices, the water reuse facility can ensure the safety and sustainability of operations and build public confidence in the safety of water supply. The detailed public and stakeholder communication and engagement strategy is outlined in Chapter 9.

Table 4-8: Plant Operation Documentation

Documentation	Short Description	Current Status
Reuse Plant Operational Procedure	SOP for the reuse plant, ensuring the safe and efficient operation of the facility while maintaining compliance with all regulatory requirements.	Available
Rapid Sand Filter Backwash	To ensure the effective and efficient backwashing of rapid sand filters	Available
GAC backwash	For the proper backwashing of the GAC filters	Available
UF Backwash, CEB and CIP system	Clear guidelines for the proper backwashing, cleaning, and chemical enhanced backwashing of the UF membranes	Available
Drawings	To provide graphical representations of the plant with detailed information for efficient plant operation, and management Process Flow Diagrams, GA Layouts, Electrical and wiring diagrams, P&IDs, Civil and mechanical drawings	Available
Emergency Protocol and Emergency Contact List	Establish effective and efficient emergency response protocol for the safety of personnel, property, and protection of the environment, and the continued operation of critical systems during emergencies. This document is also the Darvill WWTW working document.	Available
Training Manuals and Schedules	Knowledge Transfer and consistent operation of the plant	Available
Water quality on Log sheets and operators log book	Daily monitoring is recorded on log sheets and logged onto the computer. A log book is used for recording everything that was done during a shift	Available and in use
Sampling Procedures	There is an existing UUW organizational document for sampling. These processes also ensure that cross contamination prevention for operators is taken into account.	Available
Reporting procedures	Results for plant monitoring that is conducted by the UUW laboratory is stored on LIMS.	Available
First aid and injury records; Investigation reports on previous hazardous events; Workplace inspection reports; Record of hazardous substances and Material Safety Data Sheets.	These documents are already working documents since the FERDP is a part of Darvill WWTW.	Available and in operation

4.8 SUMMARY

The WRSP developed for the Darvill FERDP places a primary emphasis on ensuring the safe operation of the envisioned water reuse treatment system. The core objective was to mitigate the risk of adverse health and environmental consequences for the general public, on-site staff, and potential beneficiaries. This plan encompasses a thorough risk assessment matrix encompassing all components and sub-components associated with the FERDP. The summarized results is presented in Table 4-9 (a more detailed table is provided in Appendix A). It provides a comprehensive overview of the potential hazards and hazardous events relevant to the reuse plant. These hazards encompass a wide range of concerns from the catchment to the treatment processes. The systematic assessment that classified the hazards based on their likelihood, severity and inherent risk scores allowed to understand and identify which potential hazards pose the greatest threats and need immediate attention. The assessment also emphasize the importance of proper maintenance, monitoring and control measures to prevent potential failures in the reuse plant. It is evident that the plant has implemented multiple control measure and preventative actions to address these hazards. However, the effectiveness of the measures in place vary and residual risks are still present. Therefore, continuous monitoring, maintenance, improvement of control measures and frequent revision of the WRSP are imperative to maintain the water quality standards for safety.

It is important to review and update the WRSP to ensure the continued safe operation of the DPR plant and production of quality potable water. Planned periodic review of the WRSP to incorporate new information, lessons learnt and plant upgrades, audit findings and user and operators feedback. In addition, the WRSP will be reviewed after a significant incident, near miss or emergency, and update as required. The updated WRSP must be shared with the relevant stakeholders. In summary, the review and updating of the WRSP will be comprehensive and ongoing effort to ensure the safety of humans and the environment. It will involve collaboration, risk assessment, monitoring, and continual improvement to adapt to changing conditions, regulations and emerging challenges in the realm of water supply and safety.

Table 4-9: Summary of Hazard and Risk Analysis for Darvill FERDP

System	Sub-system	Hazard/Hazardous event	Is this hazard likely to lead to a risk to DPR plant?	Hazard Description	Frequency / Severity/Inherent risk score	Control/Preventative Measure	CCP Parameters/Limits	Control Effectiveness	Residual Risk Score	Residual Risk Priority
Catchment of Darvill Wastewater Works		Wastewater discharges due to leaks in sewer reticulation system	Y	Leaks due to damaged infrastructure, broken pipelines, malfunction of valves	5/4/20	Reactive maintenance teams, Routine weekly monitoring by UUW and municipal environmental health staff, Sewerage Inspectorate, Call centre, DUCT reporting, MIG budget approved for infrastructure replacement, CCTV inspections.	-	50%	10	High
		Industrial discharges into sewer system	Y	Discharge of unauthorised chemicals, effluents that exceed allowable limits, excessive discharges or shock loads	5/3/15	TE monitoring & inspections, Permits from industries, TE bylaws (updated June 2014), flow monitoring project in collector sewers, online monitoring	-	75%	3,75	Low
		Failure of screening at pump station	Y	Large objects may pass through, damage to downstream equipment, adversely affects the treatment process	3/4/12	Sewer cover replacement project to prevent dumping of large objects, public awareness	-	50%	6	Medium
Darvill Wastewater Works Main Plant Process		Lack of calibration and maintenance of inflow meters	Y	Incorrect readings or no readings, optimisation of plant is compromised.	5/4/20	Annual calibration of flow meters. Estimation of inflow by using the outflow meter since the inflow is not operational. Gauge plates on the outflow. Reactive maintenance in place in case of failures.	-	30%	14	High

		Plant inflow exceeds design capacity	Y	Excess inflow to the plant – overloading of plant infrastructure, inadequate treatment of wastewater	5/5/25	Storm dam and balancing tank, process optimisation, some of the new units are in operation, side spill and channel, extra chlorination & Storm dam return	-	30%	17,5	Very High
		Poor tracking of maintenance	Y	Lack of timeous maintenance, delays in service and spare parts orders	3/4/12	SAP job notification status, Liaison meeting between Superintendent and asset management staff.	-	70%	3,6	Low
Darvill Direct Potable Reuse (DPR) Plant	Inlet works	Antibiotics	Y	High concentration of antibiotics entering Darvill WWTW Influent (veterinary and human antibiotics – azithromycin, etc.)	5/4/20	Activated Sludge 10-50% removal Coagulation, Clarification, Rapid Gravity Filtration Plant <20% removal Ultrafiltration >90% removal GAC Filtration > 90% removal Ozonation > 95% removal Chlorination > 80% removal	-	70%	6.0	Medium
		Pharmaceuticals and metabolites	Y	High concentration of Pharmaceuticals entering Darvill WTWW Influent (Antibacterials (sulfamethoxazole), analgesics (acetominophen, ibuprofen-IBP), beta-blockers (atenolol), antiepileptics (phenytoin, carbamazepine-CBZ) PCT)	5/4/20	Coagulation, Clarification, Rapid Gravity Filtration Plant <20% removal Ultrafiltration >90% removal GAC Filtration > 90% removal Ozonation 50-80% removal Chlorination 20-50% removal	-	50%	10,0	High
		Hormones	Y	High concentration of Hormones entering Darvill WTWW Influent (e.g. estrone, 17 B-Estradiol, 17a-ethinylestradiol, testosterone, progesterone)	5/4/20	Ultrafiltration >80% removal Coagulation, Clarification, Rapid Gravity Filtration Plant <20% removal GAC Filtration > 90% removal Ozonation > 95% removal Chlorination > 80% removal	-	90%	2,0	Low
		Transformation Products	Y	High concentration of transformation products entering Darvill WTWW Influent (N-Nitrosodimethylamine – NDMA,	3/4/12	Activated Sludge <20% removal Coagulation, Clarification, Rapid Gravity Filtration Plant <20% removal	-	50%	6,0	Medium

				Haloacetic acids-HAAs, trihalomethanes-THMs)		Ultrafiltration >90% removal GAC Filtration > 90% removal Ozonation 50-90% removal Chlorination <20% removal				
		Personal care products (PCPs)	Y	High concentration of PCPs entering Darvill WTWW Influent (triclosan, triclocarbon, sunscreen ingredients, pigments)	5/4/20	Activated Sludge <20% removal Coagulation, Clarification, Rapid Gravity Filtration Plant <20% removal Ultrafiltration >90% removal GAC Filtration > 90% removal Ozonation > 95% removal Chlorination > 80% removal	-	70%	6,0	Medium
		Pesticides, biocides and herbicides	Y	High concentration of pesticides, biocides and herbicides entering Darvill WTWW Influent (atrazine, lindane, diuron, fipronil)	3/4/12	Coagulation, Clarification, Rapid Gravity Filtration Plant <20% removal Ultrafiltration >80% removal GAC Filtration > 80% removal Ozonation > 80% removal Chlorination <20% removal	-	50%	6,0	Medium
		Industrial Chemicals	Y	High concentration of industrial chemicals entering Darvill WTWW Influent (1,4 Dioxane, flame retardants, methyl tertiary butyl ether, tetrachloroethane)	3/4/12	Activated Sludge % removal TBC Coagulation, Clarification, Rapid Gravity Filtration Plant % removal TBC Ultrafiltration >90% removal GAC Filtration > 90% removal Ozonation > 95% removal Chlorination > 80% removal	-	50%	6,0	Medium
		Pump Failure	Y	Failure of duty pump – no inflow to plant	2/4/8	Standby available; flowmeter	-	90%	0,8	Low
		Power Failure	Y	Power outage/loadshedding – no inflow to plant	3/4/12	UPS triggers closure of inflow valve	-	50%	6	Medium
	Coagulat ion & Flocculat	Incorrect chemical dosing	Y	Insufficient/no/overdosing of chemicals due to failure of dosing pumps, valves, or blockages in	3/4/12	Standby dosing pump; process control instrumentation; operational monitoring	-	90%	1,2	Low

				the system – affects final water quality						
		Chemical leaks/spills	Y	Loss of containment due to equipment/instrumentation control failure; pipe rupture/leak; human error	3/5/15	Bund walls; drainage systems; process control instrumentation; operational monitoring	-	70%	4,5	Low
		Poor chemical quality	Y	Affects final water quality	2/4/8	Chemical quality checks (COAs)	-	95%	0,4	Low
	Sedimentation	Lamella clarifiers not able to achieve desired solid separation (< 5 NTU)	Y	Solids overloading of clarifiers due to inadequate desludge regime; damage to lamella plates (reduced separation efficiency)	4/4/16	SOPs; operational monitoring; online turbidity meters; planned maintenance schedule	Turbidity of clarified water: < 5 NTU	60%	6,4	Mediu m
		Failure in desludge system	Y	Desludge valve failures; compaction of sludge in hoppers (ratholing); affects clarified water quality	4/4/16	SOPs; operational monitoring; online turbidity meters; planned maintenance schedule	Turbidity of clarified water: < 5 NTU	60%	6,4	Mediu m
		Improper/irregular maintenance of lamella plates	Y	Uneven flow distribution; sludge compaction on lamella plates; solids carryover in clarified water – poor clarified water quality	2/4/8	SOPs; operational monitoring; online turbidity meters; planned maintenance schedule	Turbidity of clarified water: < 5 NTU	65%	2,8	Low
	Rapid Gravity Sand Filtration	Backwash sequence failure	Y	Failure of backwash pumps and valves; affects the filtrate quality	3/4/12	Operational monitoring, SOPs, planned maintenance schedule	Turbidity of filtrate: < 0.5 NTU	80%	2,4	Low
		Overloaded filters	Y	Poor filtered water quality	3/4/12	Operational monitoring, SOPs, planned maintenance schedule	Turbidity of filtrate: < 0.5 NTU	60%	4,8	Low
	Ozone Dosing System	Leak/rupture in ozone system	Yes	Insufficient/no disinfection and poses health risk to staff personnel	3/5/15	Ozone gas leak detectors, planned maintenance, operational & online monitoring, safety checks during startup procedure	-	90%	1,5	Low
	Granular Activated Carbon (GAC) Filtration	Insufficient backwashing	Y	Overloaded filters – Affects final water quality	3/5/15	Operational and online monitoring, SOPs, process optimisation	-	80%	3	Low
		Spent GAC	Y	Lower rates of adsorption in GAC filters, adversely affects filtration process/efficiency and final water quality	2/5/10	Operational and online monitoring, SOPs, process optimisation	-	75%	2,5	Low

	Ultrafiltration & OSEC	Poor flushing of cleaning chemicals from membranes	Y	Contamination of final water	2/5/10	Planned maintenance, CIP procedure, operational and online monitoring	Turbidity of filtrate: < 0.1 NTU	70%	3	Low
		Poor quality of filtered water	Y	Blocked strainer on UF feed line, fouled membranes; deterioration of membranes; affects final water quality	2/5/10	Planned maintenance, operational monitoring, SOPs, process optimisation	Turbidity of filtrate: < 0.1 NTU	70%	3	Low
		Process equipment failure	Y	No OSEC disinfection – impacts final water quality	2/5/10	Planned maintenance, operational and online monitoring, O&M manual, safety checks	Turbidity of filtrate: < 0.1 NTU; Free chlorine: < 5 mg/L E. coli: Not detected; Total coliforms: ≤ 10 MPN or cfu/100 mL	80%	2	Low
		Leak/rupture in system	Y	Insufficient/no disinfection and poses health risk to staff personnel	3/5/15	Planned maintenance, operational & online monitoring, safety checks during startup procedure	Turbidity of filtrate: < 0.1 NTU; Free chlorine: < 5 mg/L E. coli: Not detected; Total coliforms: ≤ 10 MPN or cfu/100 mL	90%	1,5	Low

	Storage	Contamination of final water, storage capacity limitations, final water not meeting chlorine limits.	Y	Sediments on reservoir that can result in water quality failures, inadequate cleaning of reservoirs and ingress of stormwater causing contamination. Plant operating above capacity, reservoir levels not adequately monitored and over or under dosing chlorine.	4/4/16	Cleaning schedule for reservoir, planned maintenance, operate reservoirs between acceptable limits. SOPs for monitoring storage reservoirs.	Free chlorine: < 5 mg/L; pH: ≥ 5.0 to ≤ 9.7; E. coli: Not detected; Total coliforms: ≤ 10 MPN or cfu/100 mL	70%	4,8	Low
	Distribution	Water not meeting final water quality limits and loss of water in the system	Y	Turbidity OORs due to inadequate cleaning, chlorine OORs due to over/ under dosing or inadequate contact time. Vandalism to reservoir covers and pipes leading to loss of water. Theft of valves.	4/4/16	Planned maintenance, security, process monitoring.	Free chlorine: < 5 mg/L; pH: ≥ 5.0 to ≤ 9.7; E. coli: Not detected; Total coliforms: ≤ 10 MPN or cfu/100 mL	60%	6,4	Medium
Organisational		Lack of maintenance staff	Y	Inadequate maintenance to process equipment due to understaffed maintenance team	2/4/8	New appointments for vacancies	-	60%	3,2	Low
		Lack of process controllers, operators	Y	Site understaffed	3/4/12	Staffing Regulation 17	-	60%	4,8	Low
		Process controllers, operators lack adequate skills	Y	Personnel do not meet level of qualification required for the position	3/4/12	Staffing Regulation 17	-	60%	4,8	Low
General		Lack of closure to water quality failures	Y	Quality of water not meeting required standards for process units/overall process – cause unidentified	3/4/12	Corrective & Preventative Actions (CPAs) procedure; process monitoring; site P&Q technician	-	65%	4,2	Low

		Natural events (flooding, storms, hail, etc.)	Y	Adverse weather conditions	3/5/15	Weather forecast updates circulated across organisation	-	40%	9	Mediu m

CHAPTER 5: EVALUATION OF THE FERDP PERFORMANCE

5.1 INTRODUCTION

One of the most commonly used indicator to measure the performance of a water reuse plant is the removal efficiency of pollutants. The pollutants in wastewater include organic matter, nitrogen, phosphorus, and other trace elements. The removal efficiency of these pollutants is an essential factor that determines the quality of the treated water. Another essential indicator of a water reuse plant's performance is the quality of the treated water. The treated water must meet the required standards to be suitable for its intended use. The World Health Organisation (WHO) has established guidelines for water quality for reuse. The guidelines include parameters such as microbial indicators, trace elements, and organic pollutants. In a study conducted by Wang et al. (2015), the performance of a water reuse plant in China was evaluated using different treatment processes. The study found that the plant's removal efficiencies for total suspended solids (TSS), biochemical oxygen demand, and chemical oxygen demand (COD) were 98.8%, 97.6%, and 95.1%, respectively.

The reliability of a water reuse plant is also essential to ensure continuous operation and minimise downtime. The plant must be designed with redundant equipment and backup systems to ensure uninterrupted operation. The type of treatment process used in a water reuse plant also affects its performance. It is essential to strive for continuous performance and compliance with targets in any water recycling scheme. Faults and incidents may occur in the operation of any water treatment plant, and therefore controlled and timely responses must be carried out to prevent these events from posing a risk to public health or requiring public notification. To ensure public and environmental health and maintain the supplier's reputation and users' confidence in recycled water, protocols must be established for dealing with identifiable events such as power outages, equipment breakdown, monitoring criteria exceedance, and consumer dissatisfaction. Since some incidents cannot be anticipated, utilities must be prepared to "expect the unexpected." When such incidents occur, the organisation must be able to adapt to the circumstances and respond constructively and efficiently (Swartz, et al., 2022).

The performance of a water reuse plant can be evaluated using several indicators, including removal efficiency of pollutants, quality of treated water, energy consumption, and reliability. The indicators required to evaluate the overall plant performance of the Darvill FERDP include pollutants removal efficiency, quality of treated water, and reliability (downtime) of the process equipment. Contaminants of emerging concern (CECs) encompass a diverse group of substances that are not currently regulated under existing water quality standards but are increasingly recognized as potential threats to human and environmental health. These contaminants originate from various sources, including pharmaceuticals, personal care products, pesticides, and industrial chemicals (Falakh & Setiani, 2018; Abafe et al., 2018). Their rising use and production have led to widespread occurrence in the environment, notably in surface water, groundwater, and drinking water supplies (Swartz et al., 2018; Swanepoel et al., 2015).

Pharmaceuticals are a significant category of CECs due to their prevalent use and subsequent entry into the environment through wastewater treatment plants, landfills, and other disposal methods. These substances can persist in the environment, accumulating in sediments, soils, and water bodies, thereby impacting human and wildlife health. Commonly detected pharmaceuticals include non-steroidal anti-inflammatory drugs (NSAIDs), antibiotics, antidepressants, and hormones. Their presence in aquatic environments has been linked to altered behaviors, reproductive success, and growth rates in aquatic organisms. Moreover, long-term exposure to low concentrations of pharmaceuticals has been associated with the development of antibiotic resistance in bacteria (Mhuka & Dube, 2020; Malnes et al., 2022).

In South Africa, pharmaceuticals are a primary source of CECs due to the high usage of medication. Various studies have documented the presence of pharmaceuticals, pesticides, and industrial chemicals in South African water bodies, highlighting the pervasive nature of these contaminants. For example, a study by Rimayi et al. (2018) found several pharmaceuticals, including antibiotics and ARVs, along with pesticides and steroid hormones, in the Hartbeespoort Dam catchment and Umgeni River. Personal care products (PCPs) also contribute significantly to CECs, containing chemicals like fragrances, preservatives, and antimicrobials (Malnes et al., 2022). Similarly, pesticides such as atrazine, glyphosate, and chlorpyrifos, along with industrial chemicals like polyfluoroalkyl substances, bisphenol-A (BPA), and phthalates, persist in the environment and accumulate in sediments, posing various health risks (Anderson et al., 2021; Maddela et al., 2022).

A recent study in South Africa reported the presence of CECs in drinking water from major cities over four seasons, with herbicides atrazine and terbuthylazine, and the anticonvulsant drug carbamazepine being the most frequently detected. However, the levels were below the maximum levels recommended by the World Health Organization and the US Environmental Protection Agency, indicating that the drinking water was safe for consumption (Shehu et al., 2022). The increasing recognition of CECs' risks has spurred efforts to monitor and regulate these substances. This study aims to analyze and identify the types and quantities of targeted CECs present in the final effluent of Darvill Wastewater Treatment Works (WWTW) and at different stages of the FERDP treatment processes, assessing their removal efficiency.

5.2 METHODOLOGY

5.2.1 Water Sampling Monitoring Programme & Operational Monitoring

Key water sampling points were identified at the Darvill FERDP (refer to Chapter 4) and a monitoring programme was established for microbial and chemical water quality analyses. The water samples are to be collected by sampling officers on site and thereafter delivered to uMngeni-uThukela Water Laboratory Services. In addition, process operators are required to conduct two-hourly water quality monitoring on site for turbidity and free and total chlorine concentrations, to be captured in a daily monitoring log sheet (refer to Chapter 4).

5.2.2 Chemical Optimisation Process for the HP Wash Plant

5.2.2.1 Sample Collection, Storage and Water Quality Analysis:

The head of works at the conventional treatment section, also referred to as the “High Pressure (HP) Wash” plant, was designed to allow for the dosing of two coagulants – polyelectrolyte and aluminium sulphate. A standard jar test procedure was followed by the operators to determine the optimum coagulant dosages to be implemented on site. Treated, unchlorinated wastewater effluent samples were collected using the grab sampling technique. The point of sample collection is selected to be the final effluent channel for Darvill WWTW, specifically the inlet point, as the effluent enters the channel with sufficient velocity to keep the solids in suspension. Sampling containers (25 litre) are rinsed three times prior to sample collection and the rinse water is to be discarded further downstream to avoid contaminating subsequent samples. The samples will be stored in a cold room at 4 °C prior to laboratory analyses.

5.2.2.2 Polyelectrolyte test:

The polyelectrolyte solution used to conduct jar tests will be prepared by weighing out 0.80 g of polyelectrolyte and transferring to a 1 litre volumetric flask. The flask is then diluted to mark using deionised water. This test is carried out using six glass beakers (800 mL) for the wastewater effluent sample. Each sample is well mixed before transferring into the beakers. The polyelectrolyte solution, with a dosing range of 1 to 6 mg/L (using increments of 1 mg/L), is added to the beakers using chemical syringes. The flash mix speed on the 6-paddle jar stirrer is set to 250 rpm and the samples are allowed to stir for 2 minutes, followed by slow mixing at 40 rpm for a further 15 minutes. These mixing speeds were selected to mimic the operation of the mechanical mixers on site. After leaving the samples to settle for 15 minutes, each sample will be filtered into 1000 mL conical flasks using 4-12 µm filter paper. The turbidity of the filtered samples will be measured and recorded. Based on the results, the optimum polyelectrolyte can then be selected.

5.2.2.3 Aluminium sulphate test:

The aluminium sulphate solution used for conducting jar tests is prepared by weighing out 1.67 g of aluminium sulphate (48% solution) and transferring to a 1 litre volumetric flask. The flask is then diluted to mark using deionised water. This test follows a similar process used for polyelectrolyte optimisation, using the same wastewater effluent sample. Each sample is well mixed before transferring into the 800 mL beakers. The optimum polyelectrolyte dosage is added to each beaker and the samples will be stirred for 2 minutes at 250 rpm. Thereafter aluminium sulphate solution, with a dosing range of 5 to 25 mg/L (using increments of 5 mg/L), is added to the beakers using chemical syringes. The flash mix speed on jar stirrer is set to 100 rpm and the samples are allowed to stir for 2 minutes, followed by 40 rpm for a further 15 minutes. After the samples settle for 15 minutes, each sample will be filtered into 1000 mL conical flasks using 4-12 µm filter paper. The turbidity of the filtered samples is measured and recorded. Based on the results, the optimum aluminium sulphate dosage can be selected.

Figure 5-1: Set-up for Standard Jar Test Procedure

5.2.3 Assessing Indicative Removal of CECs

The primary objective of this research was to evaluate the effectiveness of the advanced treatment processes, and the study focused on the system's ability to remove microorganisms and certain contaminants of emerging concern (CECs) from the incoming water. To this end, water samples from the key sampling points (prior to treatment, following each treatment stage, and in the final treated output) were analysed for contaminant concentrations and thereafter removal efficiencies were determined. The intended operation for the FERDP was to run the HP Wash plant along with each one of the two process configurations of the ATP (as described in Chapter 3) and to assess the performance in terms of contaminant removal efficiency. The treatment objectives and technology implemented on site is described in Table 5-1 below.

Table 5-1: Treatment Objectives and Implemented Technology

Treatment Objective	Implemented Technology
Reduction of TOC	Addressed by UF, GAC filtration and AOP.
Removal of toxic substances	Addressed by UF, GAC filtration, AOP and OSEC.
Reduction of inorganic nutrients	Addressed by the HP Wash plant (specifically, coagulation/flocculation and lamella clarification).
Multiple barriers	Addressed by the implementation of multiple unit operations/processes and online monitoring.
Produce water compliant with SANS 241: 2015 standards	Addressed by all of the treatment technologies installed on site and online quality monitoring.

The removal efficiency (T_e) of major pollutants plays an integral part of the performance evaluation of the treatment process. This efficiency will be calculated for each water quality parameter using equation 5-1 below.

$$T_e = \frac{Influent\ concentration - Effluent\ concentration}{Influent\ concentration}\ x\ 100 \qquad (5\text{-}1)$$

Sample collection involved using 200 mL Duran glass bottles, which were rinsed with deionized water, methanol, and water. Grab samples were taken in triplicate before and after the high-pressure (HP) wash plant, ultrafiltration (UF), advanced oxidation processes (AOP), and granular activated carbon (GAC) filtration units. Additionally, a 24-hour composite sample of the influent was collected. Control samples were also collected to ensure accuracy and reliability.

The collected samples were transported to the laboratory and processed within 48 hours. Samples were allowed to settle before 100 mL were decanted into a clean sampling bottle, where the internal standard was added. These samples were then transferred onto solid-phase extraction (SPE) cartridges for analysis. The cartridges were conditioned and processed under reduced pressure using a pump, then shipped to Umea University for further analysis.

The LC-MS/MS analysis of extracted samples was conducted using reversed-phase liquid chromatography (RP-LC) followed by ionization of the analytes with heated electrospray ionization (HESI) in positive polarity mode. Mass spectrometric (MS) detection was performed using a triple quadrupole MS/MS system. Separation was affected on a C18 Hypersil Gold column with ultrapure water and HPLC-grade methanol as eluents.

5.3 LIMITATIONS

5.3.1 Process Unit Downtime

Due to delays in attending to operational issues during the commissioning phase and other challenges (as outlined in Chapter 4), continuous operation of the two intended process configurations for the ATP was not achieved. The site was also affected by power outages/loadshedding. Figure 5-2 provides an indication of the downtime (%) for each process unit/section.

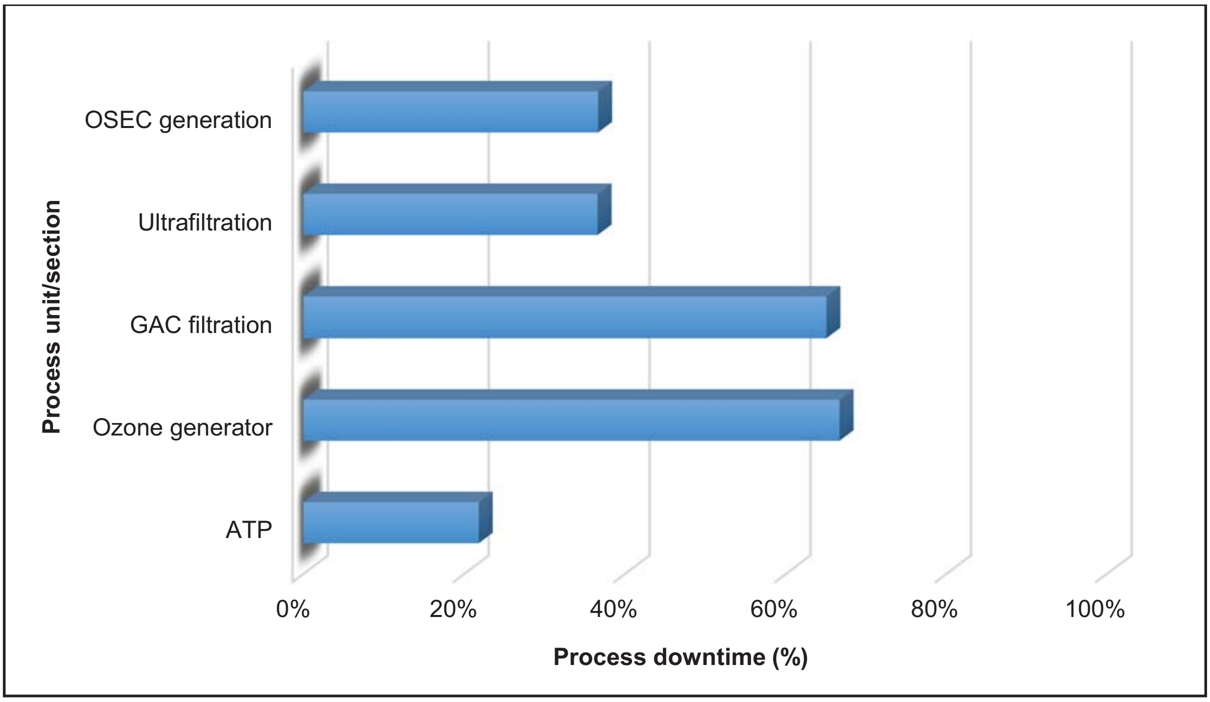

Figure 5-2: Downtime (%) for Process Unit/Section at the FERDP

As illustrated in Figure 5-2 above, the ozone generator and GAC filters accounted for the highest downtime (± 65-67%). This was primarily due to failure of the GAC feed pumps installed on site. The contractor established that pump failure was due to the pumps being undersized for the GAC filtration system. As a result, the AOP process (ozone generation system and H_2O_2 dosing system) was also offline as the system is interlocked with the GAC filtration system. Similarly, post-chlorination via the OSEC dosing system is interlocked with the UF system; hence, similar downtime (± 37%) was noted for these systems as seen in Figure 5-2. In the event of process unit failure, external contractors are required to assess and rectify on site. In addition, the turnaround time for addressing process unit failure is also dependent on the availability of the suppliers of process equipment.

5.3.2 Laboratory Resources

The designated laboratory to conduct all water quality analyses as per the monitoring programme is uMngeni-uThukela Water's internal laboratory located in Pietermaritzburg. The Laboratory Services department was advised on the sample requirements in advance to confirm that the laboratory is fully resourced to support the required turnaround-times for analyses. However, those posed to be a challenge due to the laboratory also being responsible for daily analysis of water samples for all water and wastewater treatment plants operated by uMngeni-uThukela Water throughout the KwaZulu-Natal province, as well as for conducting water sample analyses for external clients. In addition, the two-hourly routine sampling conducted on site by operators can only be conducted for a very limited number of water quality parameters (turbidity, free chlorine and total chlorine). This was due to lack of availability of other laboratory testing equipment that will allow for testing of a wider range of water quality parameters (e.g. colorimeter, spectrophotometer).

5.3.3 Analysis of CECs

The analysis of CECs was limited by the analytical capabilities available within South Africa. This necessitated a focus on specific CECs based on their prevalence and the availability of detection and quantification methods. Additionally, local laboratories were unable to accommodate our samples at the time, requiring us to send samples abroad for analysis, which resulted in significant delays.

5.4 NOTE ON WATER QUALITY RESULTS

All water quality results were assessed against the South African National Standards (SANS) for Drinking Water (SANS 241: 2015). This will provide an indication as to how effectively the combination of advanced technologies used for direct potable reuse can treat water to SANS 241: 2015 specifications. Due to the limitations discussed below, the results will not be presented in this report. These will be published once verified and accurate results are available.

However, based on the available data, the findings thus far are promising. The multibarrier system demonstrated effectiveness in eliminating a diverse range of CECs for most substances targeted in this study. However, to draw more robust conclusions, additional data needs to be collected through continuous sampling, analysis, and evaluation of the treatment technology in place. Therefore the results will not be published at this stage, this process will continue to ensure comprehensive assessment of the treatment process to confirm results.

5.5 RECOMMENDATIONS AND FUTURE WORK

The following recommendations are made with regards to water quality testing at the FERDP:

- Due to the excessive amount of water sampling analyses required for a research project of this nature, outsourcing water quality testing to an accredited laboratory with the capacity to conduct frequent testing of water samples should be considered. This will assist in reducing the turnaround time for water quality results
- Explore Seasonal Variations: Investigate the presence and levels of CECs across various environmental conditions, including seasonal variations and weather patterns.
- Expand Target List: Expand the existing list of targeted CECs to include a wider range of pharmaceuticals and other emerging contaminants such as disinfection byproducts (DBPs), transformation products, microplastics, hormones, and pesticides to provide a more comprehensive understanding of the contamination landscape.
- Develop Local Capacity: It is critical to develop local human capacity and in-house analytical methods to enhance the frequency and scope of analysis and the dependability of data.
- Invest in Infrastructure: Prioritize investment in equipment and training for CEC analysis throughout the country's laboratories and universities to support scaling up and the implementation of the reuse plant at a nationwide level.
- A dedicated laboratory space should be installed at the Darvill FERDP, fully equipped with monitoring equipment such as colorimeter or spectrophotometer that allows for testing of a wider range of water quality parameters. This will assist in reducing the quantity of samples sent to UUW Laboratory or any external laboratory and, ultimately, increase turnaround time for water quality results.

CHAPTER 6: OPERATIONAL AND MAINTENANCE REQUIREMENTS

6.1 INTRODUCTION

One of the aims of this project was to establish the operating and maintenance requirements for running a direct potable reuse (DPR) plant in the South African context. Water reuse plants are relatively new and currently, there are no official protocols or educational courses that are specifically geared towards direct potable reuse. As such, the demonstration plant installed at Darvill WWTW was intended to be a learning experience for the bulk water supplier, uMngeni-uThukela Water, and to allow the sharing of this knowledge to empower other municipalities and bulk water suppliers who may want to implement DPR in the future. The information in this section was developed from the experience of operating the Darvill Final Effluent Reuse Demonstration Plant as shown in Figure 6-1 (FERDP).

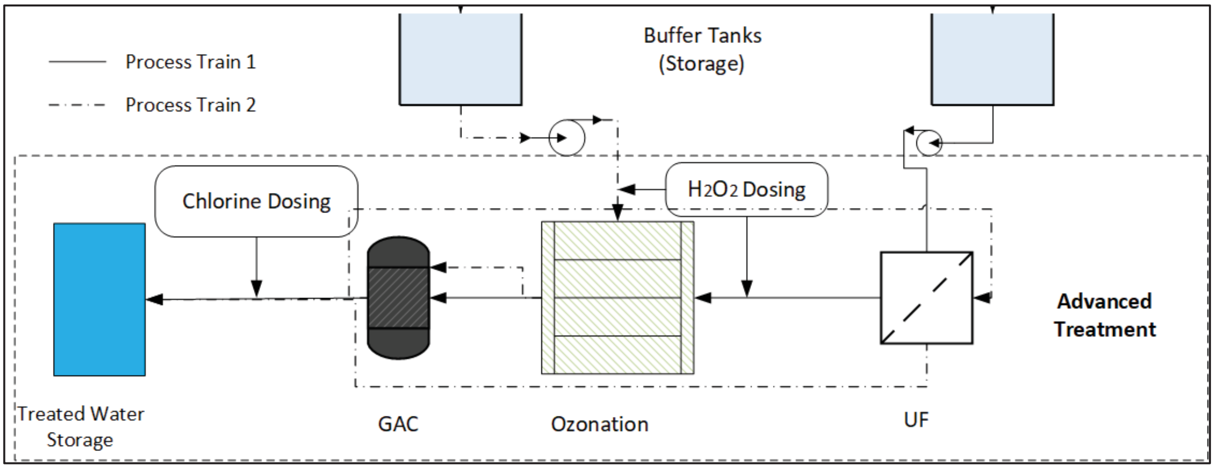

Figure 6-1: Advanced Treatment Process at the FERDP

6.2 OPERATIONAL SKILLS

The operators that work on a DPR plant must have the relevant qualifications, skills and training to operate a water and/or wastewater treatment in accordance with the regulations set out in the Water Services Act 108 of 1997. Additional training in advanced treatment processes is required for operation of a DPR plant. Since operators may be retained from the wastewater works, it is imperative that this training be comprehensive and new employees should have sufficient training before they are assigned key responsibilities (Swartz, et al., 2022). The Darvill FERDP is in operation for 24-hours daily hence; an operator is required on site at all times. Complex equipment such as the ozone generator requires constant monitoring. A gas leak is a health and safety issue. In the case of a gas leak an operator intervention would be required and, in a worst case scenario, the ozone generator would need to be shut down and all personnel in the building and vicinity should be evacuated. Final water is produced to meet drinking water standards hence the plant must be monitored throughout its operation, since any deviation that causes failures in compliance with final water quality standards needs swift corrective action. The plant is operated based on 12-hour rotational shifts and two operators are necessary per shift. One operator should be monitoring and controlling plant operations via the SCADA interface while the other operator conducts sampling and site walkabouts. This ensures that any operational or safety issue can be addressed immediately. Operators should work under the supervision of a trained process technician that is stationed onsite and available on call should any complex technical issues arise.

Due to the technology involved in the treatment processes at the Darvill FERDP, an adequate understanding of the processes, operation and troubleshooting of the equipment is required which may comprise of specialised training. The level of skill required for the advanced treatment operations depends on the ease or difficulty of operation. For example, although the ozone generator unit is small and compact, safety training is essential and many operators are not familiar with the ozone generation system. Due to the hazardous nature of the process, it is imperative that operating personnel undergo safety training before assigned the responsibility to operate the ozone system (Rajagopaul & Mbongwa, 2008). Operators need to understand the ozone sensor limits and alarms in addition to distinguishing between odours associated with “residual” ozone and ozone “leak”. During plant commissioning it was observed that some operators were sceptical to conduct the ozone residual testing and panicked during times of operation and leaks, due to the associated dangers of ozone gas. Operators should be competent in doing routine tests for determining concentrations such as turbidity, free and total chlorine, iron, manganese, as well as residual ozone. The FERDP also utilises chemicals such as hydrogen peroxide, citric acid and sulphuric acid which is different to the chemicals normally used in conventional water treatment processes. Safe handling and use of these chemicals require additional training of operators. The Material Safety Data Sheets (MSDS) must be available at the chemical bays and operators must be familiar with the MSDS of all chemicals.

Operators are required to have a good understanding of how the ultrafiltration (UF) process works, the effect of feed quality on the membranes and maintenance of the membranes when the unit is not in operation (such as preservation methods). Feed is passed through the UF unit and transmembrane pressure (TMP) drives the liquid through the porous walls of the membrane. TMP is the effective differential pressure between the feed side and filtrate side of the filter membrane and it is an important parameter for monitoring the filtration unit performance. Operators need to be aware of the TMP limits as the maximum TMP will be a trigger for the Clean-in-Place (CIP) procedure which removes build-up of contaminants that cannot typically be removed by normal backwashing only (DuPont Water Solutions, 2021). Compressors play a vital role to the UF process due to all the pneumatic valves used within the system. Operators are required to manually reset the compressors and ensure that the pressure is adequate for operation of the pneumatic valves.

The ability to communicate in writing and digitally is very important. Operators will need to be literate. Recording data and referring to the logbooks and manuals is important to ensure safe operation. An operator is not aware of activities undertaken in the previous shift unless there are entries made into the logbook by the previous operator(s). It is essential to fill in logbooks hourly even when there is no major change or incident on the plant. This allows for effective record-keeping since SCADA does not trend every single change or output. Logging of records can allow for identification of faults, potential trends that could be implemented and assist in future decision making. Training should cover the importance of recording all relevant data per shift and management of these records.

The FERDP uses onsite electrolytic chlorination (OSEC) to generate sodium hypochlorite for final disinfection. OSEC is fully automated and does not require major intervention by the operator. Dosages can be changed on SCADA and the human-machine interface (HMI) on the OSEC unit is used to reset any faults and switch the machine on and off, thereafter the unit operates automatically. Adding salt to the tank requires some manual labour as the salt is packaged in 25 kg bags. Rotameters should be checked and cleaned so that readings are always visible, and in the event that a CIP process is required, it must be selected by the operator on the HMI. In addition, the operator is responsible for ensuring sufficient hydrochloric acid solution is available for the CIP process. The OSEC process requires maintenance to be conducted by an external contractor and training needs to be comprehensive for the operation of the OSEC unit to assist with troubleshooting and routine plant maintenance.

Continuous learning and development is also important for DPR systems. Decision making skills, especially under pressure, is vital when working on a DPR plant. The following has been listed by Swartz, et al. (2022) as supporting skills and capabilities: mathematics; management of instruments and meters; SCADA operation and monitoring; reporting and alarm management; operational interfaces; critical control points; and the HACCP process.

6.3 MAINTENANCE REQUIREMENTS

Maintenance on the systems and processes used at a DPR plant require specialised skills since the equipment is more complex. Swartz, *et al.* (2022) advises that at least a technologist, technician or engineer from the water supplier should have an adequate understanding and knowledge of membrane treatment processes and this could be achieved through short courses or formal training. The plant maintenance team conducts servicing and planned maintenance of pumps, compressors, mixers and blowers. The ozone generation system is a sophisticated process and the operating complexity of the ozone system requires personnel training at all levels. Operation and troubleshooting for the ozone generator can also pose a challenge and it is also advisable to have trained a technician in the process, mechanical and safety aspects. One of the challenges with the ozone generator is that maintenance and repairs has to be done by the supplier. Supplier of the ozone unit is not based in the province so lead time for service delivery is extended.

Table 6-1 shows the general requirements of some of the important maintenance tasks that is required for the process units and systems installed at the Darvill FERDP. Certain systems may require additional and more detailed or specialised maintenance and these specific maintenance manuals can be obtained from the supplier.

Table 6-1: General Maintenance Requirements (Kruger & Naidoo, 2022)

Unit Process	Maintenance Required	Consumables
Inlet works	• Clean the inlet works water chamber when necessary, for example, in the event of algae growth. • Check and service valves in the valve chamber according to manufacturer's requirements.	HTH granules for cleaning the inlet works water chamber
Dosing systems	• Dosing pump operation must be rotated regularly so that coagulant does not build up and crystallize. • Strainers should be cleaned when dirty.	Potable water for cleaning strainers
Mixers	• Hydraulic oil level should be checked regularly and replenished with the correct oil grade. • Exercise regular maintenance of the mixer and its components to ensure that it is in good working order. • Monitor for any vibration during operation and replace worn out blades/ impellers according to the manufacturer's specifications.	Hydraulic oil
Clarifiers	• The clarifier should have a cleaning schedule in place since lamella plate clarifiers are known to experience sludge compaction over time. • Valve functioning should be inspected and checked regularly as well as maintained according to manufacturer requirements.	HTH granules for cleaning the clarifiers

Unit Process	Maintenance Required	Consumables
	• Algae build-up on clarifier walls, lamella plates, weirs or channels may create taste and odour problems. This should be cleaned on a monthly basis and recorded in the monthly cleaning schedule. • The clarifier hoppers should be cleaned every 6 months or annually to prevent rat-holing	
Rapid Gravity Sand Filters	• The filtration and backwash processes are supported by critical electrical equipment, i.e. air blowers and pumps. All electric motors, pumps, blowers and moving parts should be maintained at the manufacturer's recommended frequency. • Maintenance should be carried out by skilled and certified personnel. • Filter media depth should be monitored over time and the filter should be checked for mudballs and broken nozzles. • Filter sand should be replaced when there is sand loss and the filter bed height is below the required specification. • Filter walls should be cleaned when necessary, for example, in the event of algae growth. • Ensure that the coagulant dosages are at the optimum to prevent scum formation on the filters.	• Filter sand • Pressure cleaner for cleaning filter walls
Ultrafiltration (DuPont Water Solutions, 2021)	• Built-in module integrity test routines can be initiated either manually or automatically at predetermined intervals. • All pumps and associated auxiliary equipment should be maintained at the manufacturer's recommended frequency. • Normal backwash every 60 minutes, Primary Clean-in-Place (CIP) weekly with sodium hypochlorite. Secondary CIP once a month with citric acid followed by sulphuric acid. CIP should also be initiated when TMP is above the required limit. • Daily: Check for leaks, damage and unusual noises, compressors and blowers are working, check • Pressure decay and sonic tests can be done to check for modules that require maintenance. • The filtration isolation valve requires maintenance. Air dryer: Daily maintenance • Check function of condensate drain. • Check if water is drained.	• Sodium hypochlorite • Sulphuric acid • Citric acid • One complete change of air filters • One of each size of air regulators or seal kits to suit; • Electrical/control system components: ➢ One of each type of electrical power supply; ➢ One set of replacement indicator bulbs/lamps (where applicable); ➢ Spare fuses of each size (where applicable); ➢ Replacement elements, service and/or calibration

Unit Process	Maintenance Required	Consumables
	• Test valve function (manual drainage): Press button for approx. 2 seconds (In response to longer pressing, the valve will keep opening) • Monitor pressure dew point in case of differences to normal operation. • Verify the refrigerant condenser for cleanliness. Weekly maintenance Inspection and cleaning of condensate draining system, if necessary. Yearly maintenance • Condensate drain : Replace service unit. • Leak tightness check. Periodic checks at pressure vessels • Periodic checks must be done according to National legislations and the determinations of the user. Please note: • Maintenance work must be performed at the depressurized condensate drain only. • Use only O-Rings that have been supplied by Supplier. CIP/Feed Pumps: • Replace O-rings/seals/bearings when necessary.	kits for instruments; ➢ One pressure transmitter of each type and span (if necessary) ➢ One of each PLC Power Supply, CPU and PLC I/O cards used in the system.
GAC Filtration	• Maintenance must be carried out by skilled and certified personnel. The filtration and backwash processes are supported by critical electrical equipment, i.e. air blowers and pumps. • All electric motors, pumps, blowers and moving parts should be maintained at the manufacturer's recommended frequency. • Backwashing and replacing GAC media must be carried out as per procedures provided by the manufacturer. Step-by-step instructions for GAC replacement must cover the following tasks: removing spent GAC, inspecting and cleaning of empty filtration vessels, refilling the filters with GAC media (wetting of GAC, backwash, forward rinse to waste, and return to service).	None

Unit Process	Maintenance Required	Consumables
	• These instructions must include a list of parts, tools or other equipment required for maintenance procedures, valves to be opened/closed, hose connections to be made and all other detailed steps to be taken. • Routine monitoring of target contaminants is crucial to ensure the GAC media is replaced at the appropriate frequency. • Maintenance backwash, normal backwash and flushing must take place if the system has not been used in a long time. This is to ensure elimination of any bacterial growth. Blowers: It is recommended to carry out the maintenance work on the positive displacement machine at the specified intervals by the manufacturer, Aerzener.	
OSEC (Evoqua, 2016)	• Daily checks for leaks and ensure settings are correct. • Conduct CIP with 5% HCl solution weekly or when there is a marked increase in cell voltage. • Water softener automatically regenerates, however, if water hardness degree exceeds 1° d H. (deutsche Härte = German hardness), start the regeneration procedure manually. Water hardness should be tested weekly. • Filter and flow meter to be checked for debris and contamination weekly. The following maintenance procedures are recommended: Rectifier: • Clean the fan and the fan duct. • Check the fan for function and noise. • Check the cooling air quality. • Visually check all accessible connections. • Do not clean the rectifier using strong solvents. • Check the free blow in the hydrogen exhaust pipe and check for leaks monthly. • Operating water filter should be replaced every six months and brine filter should be cleaned every six months. • Maintenance of the NaOCl dosing pump and water softener should be serviced annually by the manufacturer's technician.	• Hydrochloric acid (HCl) • Softener maintenance kit W3T334790 (particular model number of the kit required)

Unit Process	Maintenance Required	Consumables
	• Salt tank should be cleaned regularly as decided by the operators to remove any debris in the tank.	
Ozone	• Leakage test of the pipe work and connections annually. Tightness of the system should be checked regularly. • Respiratory equipment must be checked for operability and completeness at regular intervals and replace filter element after every use in an ozone atmosphere. • Residual ozone destructors may only be maintained and repaired by qualified personnel. • When changing the catalyst material, keep the dust formation as low as possible • The concentration of ozone in the air should be monitored and the sensors checked for operability and completeness. Ozone sensor should be replaced every 6 months. • The system for monitoring the air quality in the ozone room must be checked at regular intervals and calibrated at least once a year. The service life of the sensor is 2 years (maximum). • All screws and connectors of the electrical connections must be checked for secure fastening once per year. • Filter mat in air handling unit must be checked and cleaned every 6 months and fine filter element should be checked and replaced every 6 months. • Dewpoint sensor must be calibrated every 6 months. • Non-return valve seat sealing requires replacement annually. • Flow meter viewing glass must be checked every six months. • Overall condition of the ozone system should be checked for corrosion and performance.	Valve maintenance kit
Pressure Swing Absorption (PSA)	• Daily – check operation and purity set-points. • Weekly – check the oil level, temperature, check dryer/compressor, check filter elements and check the pressure reduction valve • Biannually – Check safety valves, gas analyser and dryer/compressor • Annual Planned maintenance (PM) – safety valves, gas analyser, dryer/compressor, Check PSA generator – ANY leaks and	• Grease • O-rings

Unit Process	Maintenance Required	Consumables
	damages. Adjust/maintain according to manufacturer's procedure, Clean/re-grease process valves, Replace O-rings, Replace • Two years' PM – or every 16 000 working hours: • Replacement of top brass filters. • Replacement of main inlet pressure regulator. • Replacement of fan for control cabinet – if present. • Three years PM – or every 24 000 working hours. The 3 years PM consists from the points of annual and 2 years PM, plus: ➢ Replacement of Heavy Duty Multimach (HDM) solenoid valve block. ➢ Replacement of main inlet pressure regulator. ➢ Replacement of gas analyser. ➢ Process valve replacement. • Four years PM – or every 32 000 working hours: ➢ Same as per two years' maintenance requirements. • Five years PM – or every 40 000 working hours: The 5 years PM consists from the points of annual PM, and the following: ➢ Molecular sieve replacement is recommended. ➢ Internal inspection of process columns. • Top brass filter replacement. • Filter element – checked and replaced every six months • Tank / column maintenance: If molecular sieve is going to be replaced, inspect columns for corrosion or other damage. Replace if needed • Valve maintenance: All valves should be inspected and cleaned. All VIP (coaxial valves) / axial valves have to be lubricated within period of 12 months or after 8000 operating hours. Medical maintenance – After each maintenance check, action is required to perform measurement of gas impurities in product oxygen.	
Compressors and Dryers	Maintenance should be performed as per the recommendations below in the following priority: • Perform maintenance when indicated by the controller.	Coolant

Unit Process	Maintenance Required	Consumables
	• Perform maintenance through either hourly intervals or scheduled maintenance intervals, or annually. Adding Coolant • Stop and isolate the compressor from the external air system. Press the emergency stop (E-Stop) button. • Ensure the main power is disconnected, locked and tagged out. • Unscrew plug and fill coolant. • Close cap and check coolant levels. Draining coolant • Unscrew the coolant cap. • Screw the drain hose in and allow coolant to drain into a bottle. • Replace cap.	
Measuring Instrumentation	Measuring instruments should be calibrated as per schedule and maintenance should be carried out at the required intervals as stipulated by the manufacturer.	Calibration solutions if required

6.4 PLANNED MAINTENANCE

Table 6-2 provides information on the planned maintenance carried out by the plant maintenance and asset team of UUW.

Table 6-2: Plant Planned Maintenance

Type of work	Frequency	Resource	Tasks
Routine Inspections	Monthly	Handyman/Artisan	Fault finding and general inspection
Functional Testing	3 monthly	Trade tested artisan	Advanced maintenance, testing and condition monitoring
Advanced Condition Assessment	Annually	Technician	Advanced condition assessment, vibration, oil analysis, vibration, thermography, etc.

The tables and information that follow indicates the list of inspections that are conducted and the parameters that are recorded on site during the planned maintenance (PM). Routine job cards are done for the monthly PM. The focus is on inspection for fault finding and predicting if there could be equipment failure. If there is a failure, then there is a follow-on work order for repairs. There is also a breakdown or reactive job card where Asset Management check if the equipment showed signs of potential failure or if the repair was proactively done.

Table 6-3 is an excerpt from a UUW planned maintenance schedule, and this particular excerpt is on motors. Similar schedules are done for other equipment.
Table 6-4 shows the inspections that are carried out for pumps.

The Functional test task list for pumps which is typically done on a 3 monthly basis is listed below:

- Inform plant management of intent to perform work (> 1 hour notice).
- Obtain permission from plant management for a partial/temporary shutdown during testing.
- Open a work permit to conduct the testing with plant management.
- Maintenance to be performed on pump with reference to manufacturer's instructions.

Table 6-5 shows the parameters that are to be recorded for the pumps during functional testing.

Table 6-3: An excerpt from an UUW planned maintenance schedule for motors

Description of elements	Work type				Frequency										Responsible person/trade	Maintenance task referenced by	Task responding		
	Inspection	Condition assessment	Measurement	Service	Daily	Weekly	2 weekly	Monthly	3 monthly	6 monthly	Annual	3 yearly	5 yearly	Number of run hours			Reliability	Safety	Legislative requirement
55Kw motors																			
Unusual noise	x							x							Electrical artisan	O & M manual	x		
Bearing vibration	x		x					x							Electrical artisan	O & M manual	x		
Bearing temperature	x		x					x							Electrical artisan	O & M manual	x		
Visual inspection of equipment and condition	x							x							Electrical artisan	O & M manual	x		
Drive shaft integrity	x							x							Electrical artisan	O & M manual	x	x	
Tighness and integrity of foundation and hold down bolts	x							x							Electrical artisan	O & M manual	x		
Check coupling alignment and integrity	x		x					x							Electrical artisan	O & M manual	x		
Grease pump anti-friction bearing with BP Energrease LS3				x					x						Electrical artisan	O & M manual	x		
Strip, clean and check coupling alignment				x				x							Electrical artisan	O & M manual	x		
External cable cleating/glanding	x							x							Electrical artisan	O & M manual	x		
External cable integrity	x							x							Electrical artisan	O & M manual	x		
Load current			x					x							Electrical artisan	O & M manual	x		
Cooling fan functionality and blade integrity	x									x					Electrical artisan	O & M manual	x		
Motor heater element (functionality)	x							x							Electrical artisan	O & M manual	x		
Motor lifting eye bolts (functionality)	x							x							Electrical artisan	OHASA	x	x	
		x									x				Mechanical Foreman	OHASA	x	x	x

Table 6-4: Inspection of Pump Mechanicals

Points of Inspection	Status
General pump condition:	
• Evidence of leaks from flanges	[PASS] [FAIL]
• Evidence of oil/grease leaks from pump	[PASS] [FAIL]
• Abnormal noise or vibration	[PASS] [FAIL]
• Too much/not enough gland drip	[PASS] [FAIL]
• Unacceptable <1 drip every 5 seconds and evidence of steam	
• Unacceptable >1 drip per second	
• Thermal point scan of Drive End (DE)	
• Thermal point scan of Non-drive End (NDE)	
• Thermal point scan of Casing	
General associated equipment condition:	
• Upstream isolation valve operating correctly	[PASS] [FAIL]
• Downstream isolation valve operating correctly	[PASS] [FAIL]
• Non return valve operating correctly (freely moving)	[PASS] [FAIL]
• Safety guards in good condition and safe	[PASS] [FAIL]
• Emergency stop button in good condition and safe	[PASS] [FAIL]

Table 6-5: Pump Functionality Parameters

Parameter	Units
Hour meter reading	h
DE Bearing temperature	ºC
NDE Bearing temperature	ºC
Suction side pressure	kPa
Delivery side pressure	kPa
Non Delivery side vibration	mm/s
Delivery side pressure	mm/s

Table 6-6: Inspections for Pumps

Inspections to be conducted	Status
Evidence of leaks from flanges	[PASS] [FAIL]
Evidence of oil leaks from pump	[PASS] [FAIL]
Abnormal noise	[PASS] [FAIL]
Oil levels acceptable	[PASS] [FAIL]
Evidence of corrosion on flanges, nuts & bolts	[PASS] [FAIL]
Evidence of corrosion on pump frame	[PASS] [FAIL]
Mounting and plinth installation	[PASS] [FAIL]
Drain pipes in good condition	[PASS] [FAIL]

Table 6-7: General associated equipment condition

Inspections to be conducted	Status
Upstream isolation valve operating correctly	[PASS] [FAIL]
Downstream isolation valve operating correctly	[PASS] [FAIL]
NRV operating correctly (freely moving)	[PASS] [FAIL]
Safety guards in good condition and safe	[PASS] [FAIL]
Emergency stop button in good condition & safe	[PASS] [FAIL]

These are the following tasks performed during planned maintenance for the pumping systems:

- Replace gland packing
- Nip glands for correct drip rate
- Perform alignment of pump-motor
- Flush grease lubricated bearings and repack
- Provide feedback of testing to plant management
- Close off work permit with plant designated official
- Provide feedback of test results to line manager (foreman)
- Provide copy of measurements to Technicians for area
- Generate remedial work job cards for any problems

The advanced condition assessments are performed through an official report prepared by the technicians and routed through the Maintenance Engineers.

Motor Task List:

- Inform plant management of intent to perform work
- Provide feedback of testing to plant management
- Close off work permit with plant designated official
- Provide feedback of test results to foreman
- Generate remedial work job cards for any problems

Table 6-8 shows the inspections that need to be performed for electrical motor systems.

Table 6-8: Motor inspections

Tasks to be conducted	Parameter or Status
Record the following measurements:	
• Hour meter reading	
Perform the following inspections:	
• Abnormal noises or temperatures	[PASS] [FAIL]
• Unsafe conditions	[PASS] [FAIL]
• Cabling and gland condition	[PASS] [FAIL]
• Mounting bolts, frame and plinth condition	[PASS] [FAIL]
• Indicator lights	[PASS] [FAIL]
• Switches and buttons	[PASS] [FAIL]

Functional Testing task list on motors (3 monthly):

- Inform plant management of intent to perform work
- Open a work permit for the testing with plant
- Provide feedback of testing to plant management
- Close off work permit with plant designated official
- Provide feedback of test results to foreman
- Generate remedial work job cards for any problems

Table 6-9: Components for motor inspection

Components for inspection and recording	Status
Cabling and gland condition	[PASS] [FAIL]
Mounting bolts, frame and plinth condition	[PASS] [FAIL]
Indicator lights	[PASS] [FAIL]
Switches and buttons	[PASS] [FAIL]

Table 6-10 indicates the motor functional parameters that are to be recorded.

Table 6-10: Motor electric functionality parameters

Measurements	Units
Hour meter reading	h
Running voltage (Red)	v
Running voltage (Blue)	v
Running voltage (White)	v
Running current (Red)	A
Running current (Blue)	A
Running current (White)	A
Max start current (reset after reading), (Red)	A
Max start current (reset after reading), (Blue)	A
Max start current (reset after reading), (White)	A

6.5 TRAINING REQUIREMENTS

Training requirements from suppliers for any new installations have been outlined by uMngeni-uThukela Water (Schalkwyk, 2019) :

"Training may occur either before or after hot commissioning depending on the role of uMngeni-uThukela Water staff. If staff are assisting with hot commissioning, then this training is to take place before hot commissioning and overlap for at least two weeks after training of hot commissioning. Both the supplier and contractor staff is required. Training shall be undertaken in three sessions. These sessions will be repeated so that each session is run twice to ensure the participation of all relevant shift staff."

6.5.1 Session one:

This session will target engineers and technicians from process, instrumentation and electrical disciplines. It should cover the full control and in depth operation of the equipment and system. It should detail all settings, interlocks and modes of operation. The session shall be two days. Day one shall consist of an interactive classroom session with the correct technical personnel and the second day shall consist of onsite practical training and simulations.

6.5.2 Session two:

This session shall target Asset Management. It should cover the maintenance schedule, required maintenance and how to complete such maintenance processes. This shall also occur over two days per unit being shown, with the first day being a classroom session and the second day a practical on-site session.

6.5.3 Session three:

This session shall target Operations personnel and engineers and technicians. It should contain a description of the process, summary of process controls, ranges and consequences of each input parameter and troubleshooting of common problems. This session shall also run over two days with the first day being a classroom session and the second day a practical session.

6.5.4 Training documentation:

Each session shall have its own training manual. The manual will consist of everything that has been taught in the classroom sessions. This will act as a quick reference for the trainees. The manuals are required before the training sessions so that trainees can make notes in the manuals at both the classroom and practical sessions. A copy of the Functional Design Specification or the Operations and Maintenance manual is not acceptable as a training manual.

6.5.5 Advanced Training:

- Specific courses focusing on the onsite generation of ozone and sodium hypochlorite must be a priority for the operators and maintenance team, including expert level training on these equipment. If the local onsite technicians are trained for advanced troubleshooting and minor servicing, one may then use service level agreements for external technicians for complete breakdown and repairs as well as major services. This will avoid the tedious supply chain management process which can lead to downtime if the units are not repaired timeously.
- Membrane filtration technology for water and wastewater processes is an important course, as the FERDP utilises UF membranes.
- Since water reuse is fairly new to South Africa, collaborations and partnerships could be formed between South African universities, international universities as well as the Department of Water and Sanitation. These will allow for South African students and water professionals to gain further education and training in courses such as Water Reclamation and Reuse Course at Santiago Canyon College in California or Australia’s University of Queensland IWES course on recycled water management.
- Organisations such as the Sacramento State Water Programs offer Advanced Waste Treatment courses. The American Waterworks Association and Singapore Water Academy also offers courses in reuse (EPA, 2023).
- Personnel with an aptitude for software usage may also want to explore using carbon software that will allow for them to predict removals via GAC, schedule regeneration or replacement of GAC media and evaluate different scenarios that may occur and have plans to mitigate such outcomes, if negative.

6.6 OPERATION AND MAINTENANCE PROTOCOL

6.6.1 Practical Operations and Maintenance Plan:

6.6.1.1 Purpose:

One of the key objectives of the project was to develop an Operations and Maintenance (O&M) plan for the Darvill FERDP. This will assist to fill gaps in the water reuse sector and provide a protocol to implement good O&M practices.

6.6.1.2 Background:

Operations and maintenance forms the backbone of DPR plants. The following protocol incorporates knowledge from experience and literature to assist any water suppliers to prepare and develop O&M manual for the system. O&M manuals should be user friendly, easy to understand and should incorporate information from those who are experienced in operating water treatment plants and advanced treatment technology.
Operation Times:
The FERDP will operate for 24 hours daily and working times will consist of two 12-hour shifts of 06:00 to 18:00 and 18:00 to 06:00 on a rotational basis that has been stipulated by the bulk water supplier.

6.6.1.3 Human Resources Requirements:

It is recommended that two operators per shift with appropriate certifications in water and wastewater operation with National Qualifications Framework (NQF) Level 6 qualification in Chemical Engineering. Operators shall work under the supervision of one process technician with 3 to 5 years of experience in water and/or wastewater engineering and minimum NQF Level 7 qualification in Chemical Engineering. One foreman and one maintenance technician must be available on call and one artisan must be on shift per discipline (electrical, mechanical and instrumentation). The operators will be assisted by auxiliary staff such as general workers and cleaning staff. Currently, there is no specific classification for direct reuse plants under the National Water Act (Act 54 of 1956). However, utilising the current Schedule 1, the reuse plant would be under Class B, which requires at least a Class IV Process Controller per shift and a Class V Process Controller for supervision.

6.6.1.4 Behavioural Competencies:

The behavioural competencies required are: competent decision-making; time management; good verbal communication skills; interpersonal skills; analytical ability; attention to detail; ability to work under pressure; self-directed and results driven; well-developed team cohesion and conflict resolution attitude.

6.6.1.5 Functional Competencies:

The functional competencies required are: knowledge of water and wastewater unit processes; working knowledge of electrical, mechanical, pipeline, plant and equipment operation and maintenance; problem solving skills; computer skills in Microsoft Word and Excel; working knowledge of PLC systems; knowledge and application of relevant local and national legislation and standards applicable to water industry as well as NOSA ISO 9001 system guidelines and implementation; good report-writing skills; recording skills and record-keeping management.

6.6.1.6 Aims and Objectives:

One of the aims of this project was to develop an O&M plan. This protocol applies to DPR plants and includes the information that should be comprise an O&M plan and manuals.

6.6.1.7 Resource Requirements:

- Equipment user manuals;
- Manufacturer's O&M manuals and technical specification sheets;
- Material Safety Data Sheets;
- Commissioning and Performance Test Data;
- Function design specification document; and
- Process and Instrumentation diagram and other required drawings.

6.6.2 O&M Plan Details:

6.6.2.1 Components of Operations:

The following should be incorporated into an O&M plan (Umgeni Water, 2016) and (Mzobe & Buthelezi, 2019):

- Description of facilities: location, process flow diagrams and process descriptions.
- Points of contact: engineer, technician, operators, artisans and emergency numbers.
- Treatment processes that detail each component and its operation.
- Monitoring requirements and routine checks.
- Equipment information should be comprehensive and include the type, size, capacity and number of units.
- Start-up and shut-down operating procedures; identify and verify the sequential start-up procedure for each unit process. These steps along with the water quality requirements and testing procedures are to be documented in a Standard Operating Procedure (SOP) which must be available onsite for the operators. Some important start-up points for the reuse plant:
    - Check for process water, power supply and air from the compressors.
    - Switch on the compressors and always reset them after a power outage or shutdown.
    - Switch on all relevant dosing pumps and ensure that systems such as the ozone generator and OSEC unit are cleared of any alarms and reset to start up.
    - Check that all relevant valves are in the required on or off positions and tank levels are adequate for operation of pumps.
    - Ensure that equipment is set to manual or automatic depending on the mode of operation.
    - Ensure that the PSA unit is switched on to start-up once the compressor has reached 5 bar or greater and ozone generation will start once the dew-point reaches -55ºC or lower.
    - OSEC system must have process water, electricity supply and salt for start-up.
- O&M plan must have the normal operating procedures that includes information of the process involved, process and operating conditions, valve positions and normal dosing rates.
- Alternate operating procedures must also be stipulated such as bypassing the Advanced Treatment Plant (ATP) if the units are under maintenance or shutdown and emergency procedures such as shutting down the plant if influent parameters are excessively high beyond the treatment capability of the plant.
- Sampling, calibration and measurements.
- Quality control.
- Health, safety and environmental requirements: identified hazards, personal protective equipment requirements, immediate action plan, evacuation plan, pressure/potential energy relief, hazardous material information, alarms, trips and interlocks (refer to Functional Design Specification if defined there) and any other safety related information.
- O&M manual should also refer to the parameters that dictate when the Incident Management Protocol (IMP) is implemented.
- A troubleshooting guide for mechanical and process that lists the common issues, probable causes, controls and prevention techniques should be included in the O&M plan.
- SOPs – details the operating procedure for a specific process or equipment and includes each mode of operation, i.e. remote automatic, remote manual and local manual.

Table 6-11 is an example of a SOP template.

Table 6-11: Standard Operating Procedure Template

STANDARD OPERATING PROCEDURE	
1	Scope
2	Purpose
	Definitions
3	Responsibilities
4	Process
	INPUT ACTIVITY OUTPUT
5	Methods
5.1	Safety, health and Environmental Requirements
5.2	Operating procedure
5.2.1	Mode of Operation
5.2.1.1	Purpose
5.2.1.2	Start-up precautions
5.2.1.3	Start-up procedure
5.2.1.4	Shut-down procedure
5.2.2	Optimisation
6	General Inspections
7	Documentation
8	Records
9	References
10	Attachments

6.6.2.2 Components of Maintenance:

Maintenance of equipment is important to ensure that it is in good working order and the life of the equipment is preserved for as long as necessary. Some components of maintenance to be addressed are as follows:

- Specific maintenance work that must be carried out is stipulated by the manufacturer and/or asset management teams and will be completed according to a planned maintenance schedule.
- Adequate spare parts should be available and ordered timeously especially if they are imported to avoid equipment being offline unnecessarily.
- A record of repairs completed should be kept by the asset management team and the plant.
- The maintenance plan should include an asset register/equipment list (Umgeni Water, 2016). This is a comprehensive list itemising all equipment broken down into logical component level (pump, motor, switchgear, etc.). For each unique piece of equipment listed, a specifications listing document is required:
    - Equipment Bill of Materials (BOM):

This will contain a comprehensive listing of all maintenance significant sub-components within each piece of equipment

- Certificates, Certificates of Compliance, etc.
- Detailed maintenance schedule:
    - Component to be maintained;
    - Required maintenance task listing (minimum and optimal);

    - Required frequency of maintenance (minimum and optimal);
    - Lubrication schedule with detailed specification;
    - Spares and consumables required for this maintenance;
    - Typical measured variable;
    - Suggested skill level of maintenance personnel:
        a) Operator (functional knowledge, observation skill)
        b) Maintenance assistant (basic skill)
        c) Artisan (qualified trade tested artisan skill level)
        d) Technician (diploma skill level)
        e) Engineer (degree skill level)
- Failure modes of individual equipment and system;
- Maintenance schedule, spare parts and lubricant requirements;
- As-built and design drawings; and
- SCADA mimics

6.7 SUMMARY

- Comprehensive O&M plans from the contractors that meet the water supplier's requirements must be developed and approved and signed by the engineer.
- The bulk water supplier also needs to ensure that the in-house O&M manuals and SOPs are understandable to the operators and these also need to be comprehensive since many of the process units are new to the plant personnel.
- A copy of the plan and manuals should be available onsite and the operations and maintenance teams should acquaint themselves with the documents.

CHAPTER 7: LIFE CYCLE COSTING FOR DARVILL FERDP

7.1 INTRODUCTION

Assessing the operational status of water treatment plants is crucial for optimising drinking water production efficiency and waste management strategies. Whilst initially selecting engineering equipment and systems based solely on the lowest procurement cost may seem cost-effective, it often overlooks the substantial ownership costs involved, which can surpass the initial acquisition expenses (Ambre, et al., 2016). Therefore, decisions pertaining to equipment purchase and system construction should encompass a holistic approach, considering not only the initial costs but also the anticipated operation and maintenance expenses over the entire lifespan of the equipment. To address this, Life Cycle Costing Analysis (LCCA) has become an increasingly vital tool used for comprehensive decision-making, aiming to optimise the total life cycle cost (Ilyas, et al., 2021). The ultimate goal of the LCCA for the Darvill Final Effluent Reuse Demonstration Plant (FERDP) was to provide uMngeni-uThukela Water with a holistic view of the costs associated with a DPR plant over its lifespan, enabling the water utility to make informed decisions regarding its feasibility and long-term viability. This information will be useful to the South African water sector for planning and budgeting for DPR projects and ensuring efficient and sustainable water reuse solutions. There are various studies conducted previously on the life cycle costs related to construction, operation and maintenance of water reuse plants in South Africa. In 2015, the Water Research Commission published a report series titled "Investigation into the Cost and Operation of Southern African Desalination and Water Reuse Plants". The comprehensive study was conducted by Royal Haskoning DHV and detailed the cost, operational and maintenance (O&M) aspects of direct potable reuse plants. Table 7-1 below is an extract of the results the study conducted on the various water reuse plants.

Table 7-1: Summary of results for O&M costs for water reuse plants (Turner, et al., 2015)

	Water Reuse Plants			
Plant	Beaufort West reclamation plant	Windhoek Goreangab reclamation plant	George UF plant	Mossel Bay UF/RO plant
Size of Plant	2.1 Mℓ/d	21 Mℓ/d	8.5 Mℓ	5 Mℓ/d
Type of Plant	Reuse: Direct potable	Reuse: Direct potable	Reuse: Indirect potable	Reuse: Direct industrial
Owner	Beaufort West Municipality	Windhoek Municipality	George Municipality	Mossel Bay Municipality
Operator	Water & Wastewater Eng.	Wingoc	George Municipality	VWS (Veolia)
Operational Status	1.2 Mℓ/day	17.5 Mℓ/day	Zero production	Zero production
Completed	2010	2001	2010	2010
Capital Cost - at time of construction - Adjusted for 2014/15 - Per unit capacity	 R26.5 mill R34 mill R16.22 mill/Mℓ/day	 R122 mill R260 mill R12.38 mill/Mℓ/day	 R36 mill (plant) R46 mill R5.14 mill/Mℓ/day	 R40 mill R51 mill R10.19 mill/Mℓ/day
O&M Cost (2014/15)	R6.92/m³	R4.87/m³	R2.11/m³	R2.72/m³
Energy Use	2.07 kWh/m³	0.57 kWh/m³	0.23 kWh/m³	0.73 kWh/m³
Electricity Cost	R1.88/m³	R0.57/m³	R0.23/m³	R0.64/m³
Chemicals	R0.85/m³	R1.55/m³	R0.44/m³	R0.18/m³
Consumables	R0.50/m³	R1.00/m³	R0.50/m³	R0.50/m³
Maintenance	R1.01/m³	R0.78/m³	R0.23/m³	R0.49/m³
Staff	R1.96/m³	R0.88/m³	R0.49/m³	R0.79/m³
Laboratory cost	R0.47/m³	R0.06/m³	R0.15/m³	R0.07/m³
SHEQ	R0.23/m³	R0.03/m³	R0.08/m³	R0.05/m³

Based on this study, the 2014/15 figures for construction of water reuse plants ranged from R12-16 million per ML/day for direct potable reuse plants, and R 5-10 million per ML/day for indirect reuse plants. Operational and maintenance costs for these plants ranged from R2-7 per m^3 of product water (Kalebaila, et al., 2020). The results obtained from the study conducted by Turner, et al. (2015) can be utilized for the purpose of cost comparison concerning the LCCA results obtained for the Darvill FERDP. The study provides an indication of how well the results will compare to actual data obtained from water reuse plants that have been in operation for over a decade. Of particular interest for comparison is the data presented for Beaufort West Reclamation Plant's, as this plant is of similar capacity to Darvill FERDP, however includes the reverse osmosis treatment process. Figure 7-1 below provides an illustration of the O&M cost breakdown for the Beaufort West Reclamation Plant.

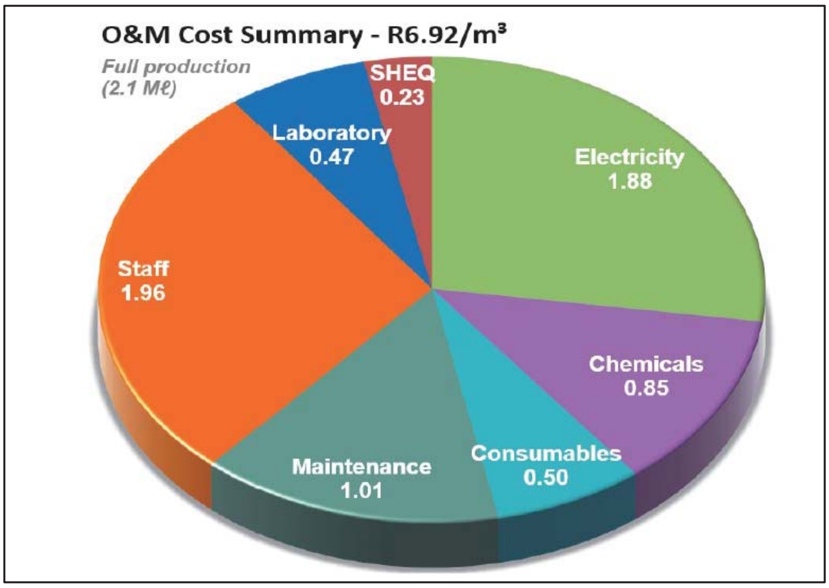

Figure 7-1: O&M cost breakdown for Beaufort West Reclamation Plant (Turner, et al., 2015)

7.2 LIFE CYCLE COSTING METHODOLOGY FOR DARVILL FERDP

The recommended protocol to conduct the LCCA is as follows:

- Record all capital expenditure costs for the plant.
- Operate the process continuously in full production mode for between 6-12 months.
- Record power consumption data and cost for the plant over this period.
- Note the chemical usage data on stock sheets daily and determine consumption costs for the following treatment chemicals:
  - Polymeric coagulant
  - Aluminium sulphate
  - Hydrogen peroxide
  - Grade 1 Coarse Non-iodated salt (used for OSEC)
  - Sodium hypochlorite (used for primary CIP of UF)
  - Citric acid (used for secondary CIP of UF)
  - Sulphuric acid (used for secondary CIP of UF).
- Consider maintenance costs incurred (in-house or via contractors) from repairs and planned maintenance.
- Include replacement costs for major maintenance items, such as UF membrane modules and GAC filter media.

- Include costs for laboratory services based on water quality testing conducted as per the monitoring programme.
- Consider human resources cost based on personnel required for operation of a direct potable reuse plant.
- Conduct LCCA using the present-value method and discount costs for a 20-year economic life.
- Perform a sensitivity analysis and scenario analyses on the components for the LCCA to determine which parameters strongly influence the project life cycle cost. Consider changes in economic assumptions such as the discount rate, inflation rates and energy use charges.

The LCCA should be conducted using the Net Present Value (NPV) method, an approach that requires all future cash flows to be converted to baseline, taking into account inflation. NPV is an economic approach for discounting future costs to their present equivalents and adding these up, taking into account the inflationary effects and the anticipated return on investment over time (Rathore, et al., 2022). NPV was calculated as per equation 7-1 below:

$$NPV = \sum \frac{Cash\ Flow_i}{(1+i)^n} \qquad (7\text{-}1)$$

Where:

i – Discount rate
n – Time period

The LCCA for Darvill FERDP will consider a 20-year economic life of the plant. The cost components to be taken into account for the LCCA of Darvill FERDP will be capital expenditure and operating expenditure (energy, chemical, maintenance, replacement, human resources, and laboratory services).

7.2.1 Capital expenditure (CAPEX) costs

The CAPEX cost comprises of all civil, mechanical, electrical installations and any other related items for engineering services during the construction of the plant. These costs will be obtained from available payment schedules for the respective contractors and subcontractors involved in the construction of the Darvill FERDP from 2016 to 2018. These costs can then be projected forward to the present year (2024) using annual average consumer price indices (CPIs). Land acquisition costs for the construction of the plant will not be taken into account as the FERDP was constructed on land already owned by UUW at the Darvill Wastewater Treatment Works.

7.2.2 Operational expenditure (OPEX)

The OPEX costs to be accounted for are energy, chemical, maintenance/replacement of key equipment, laboratory services and human resources.

7.2.2.1 Energy Cost:

The FERDP is located on the same site of Darvill Wastewater Treatment Works. The site is supplied with electricity by the Msunduzi Municipality, and billed according to the tariff structure for a Large Power User, based on time of use (TOU). Municipal bills will be used to obtain the real power consumption data (kWh and kVA) and the associated cost.

7.2.2.2 Chemical Cost:

Chemical costs will be determined using supplier invoices and chemical stock sheets for the Darvill FERDP.

7.2.2.3 Maintenance Cost:

Maintenance costs herein refers to all expenses incurred with ensuring all processes and assets are in operational condition. This includes routine maintenance activities, repairs and replacement of process components over its lifespan. Maintenance requirements for the FERDP is discussed further in Chapter 8.

7.2.2.4 Replacement Cost:

Two major maintenance costs to be considered in the LCCA (20 year evaluation period) are the replacement of UF membranes and GAC filter media at the FERDP. The respective suppliers advised that the UF membranes have a service life of three to seven years and the replacement frequency of the GAC media to be every three years. Costs for replacement of the UF membranes and GAC media will be obtained from local suppliers and factored into the LCCA, taking into account inflation rates when projecting forward over a 20 year period.

7.2.2.5 Laboratory Services Cost:

The costs associated with testing for microbial and chemical water quality parameters will be factored into the LCCA as per the current price list provided by UUW Laboratory Services.

7.2.2.6 Human Resources Cost:

The cost for human resources to operate the FERDP was based on the following staffing requirements (as discussed in Chapter 8):

- 1 x Process technician
- 1 x Maintenance technician
- 4 x Process controller/operator (2 per 12-hour rotational shift)
- 4 x Shift attendant (2 per 12-hour rotational shift)

Salary estimates were based on midpoint values obtained from UUW salary scales.

7.3 LIMITATIONS

The methodology described in Section 7.2 was to be carried out based on actual data from operating and maintaining the Darvill FERDP as per the design intent outlined in Chapter 3. Due to the constraints in operating the plant as per design intent for both process configurations (refer to Chapter 4), comprehensive actual data was not obtained for the O&M costs. The primary constraints impacting availability of actual data to conduct a detailed life cycle cost analysis were:

- Operational challenges in running process configuration no. 1 for the advanced treatment section of the FERDP;
- Delay in response to operational challenges and maintenance requirements by contractors;
- Downtime of GAC filtration process due to undersized feed pumps;
- Downtime of ozone generation unit due to servicing requirements; and
- No access to actual power consumption data for total plant or individual processes from the plant MCC due to programming issues.

In light of the abovementioned factors, an accurate, detailed LCCA could not be conducted for the FERDP.

7.4 RECOMMENDATIONS

The capital and operational costs associated with the various types of water reuse plants is significantly influenced on treatment processes and capacity of water produced on site. Sufficient planning is required at early stages of water reuse projects to ensure the lowest project life cycle cost. In order to establish the true cost effectiveness of the water reuse process implemented Darvill FERDP, a detailed life cycle costing analysis must be conducted once the challenges (highlighted in Section 9.3) are addressed and comprehensive actual data can be captured over a 6 to 12 months of continuous operation of the plant.
The following key recommendations are to be considered for a detailed LCCA of the Darvill FERDP:

- A separate meter will need to be installed for the Darvill FERDP to obtain the real power consumption data (kWh and kVA) and the associated cost.
- It is recommended that detailed sensitivity and scenario analyses be conducted on actual plant data to establish the key cost drivers for the FERDP.
- To improve upon accuracy of chemical consumption data, plant operators must ensure chemical stock sheets are updated on a daily basis and any adjustments to chemical dosages are noted timeously.
- Costs associated with water quality testing for CECs must be included in laboratory costs. This can be done once a service provider for routine CEC testing is secured along with the establishment of a routine monitoring programme for the required CECs.
- Waste disposal costs should also be considered when conducting the LCCA. All waste streams from Darvill FERDP is directed to the same balancing tank used for waste streams from Darvill WWTW. The settled sewage from this tank is dredge periodically whilst the overflow is returned to the Head of Works at Darvill WWTW. It is recommended that the in-house process design team explore options to quantify the volume of waste exiting the Darvill FERDP.
- Future work can include exploring the project life cycle costs on a scale-up reuse facility (> 10 ML/d).

CHAPTER 8: PUBLIC ENGAGEMENT AND KNOWLEDGE DISSEMINATION

8.1 INTRODUCTION

There is a significant knowledge gap with regards to the important of water reuse, the health risks, current climate crisis and public awareness (Nuhu, et al., 2020). Studies done on the public perception of water reuse show that the age, occupation, political influence and education levels of a person plays a part in whether one accepts reuse water. One of the successful projects in South Africa has been the eMalahleni Water Reclamation Plant. Although it involves the treatment of mine water to potable water standards, the community played a significant role in acceptance of the plant and the idea of drinking water purified from contaminated mine water. The community welcomed the idea of the reclaimed water largely due to their perception of the poor quality and insufficient quantity of water from the municipal water supply. A campaign was also used to prove the safety of the use of such water. Bottled water from the reclamation plant was distributed through the community for ‘taste testing’ (Sergienko, 2015). Beaufort West water reclamation was the first direct reuse plant, and initial perceptions from the public were negative. Continuous efforts were made such as campaigns with various stakeholders and scholars to visit the plant, and now there are no major objections from the public. There is also a continuous education scheme for scholars that allows them to tour the plant, taste and smell the 100% reclaimed water. Final water test results are also made available to the public (Marais & von Dürckheim, 2011). This shows that it is possible to have a direct potable reuse plant that can serve communities as long as the public understands and accepts the important of the process.

The Darvill FERDP presents an opportunity for the establishment of a national learning platform in South Africa. One of the ways to engage with various stakeholders is to allow them the opportunity to have direct access to the treatment facility, as this allows for transparency and builds trust. The FERDP building was specifically designed with the intention of being educational, as well as aesthetically appealing to all visitors. Community engagement included various levels of education, such as primary and secondary school groups, tertiary institutions and academics, the general public and community leaders. Visitors were able to view and engage with the specific selection of treatment technology, undertake plant tours, and attend presentations and visual demonstrations in a classroom environment by various specialists in the water reuse sector.

This specific design and intervention was aimed at gaining the buy-in of the public, addressing their concerns and sensitising them to direct potable reuse as being safe for consumption, and a method to resolve water scarcity as a limited resource. Social media platforms such as Facebook, Instagram and Twitter (Figure 8-14) can also play a vital role in education. Public awareness campaigns that show the public benefits of reuse are important, public health training as well as financial incentives can have a positive result on public engagement and acceptance of water reuse.

8.2 PUBLIC ENGAGEMENT PROTOCOL

8.2.1 Purpose

One of the key objectives of the project was to develop a public engagement plan for the FERDP that would address the public perceptions of direct potable reuse and reclamation and ultimately create buy-in. The purpose of the public engagement protocol is to identify the stakeholders that are impacted by the water reuse process and the ways in which the water provider can engage in public participation and gain the public’s acceptance of direct potable reuse. When communities have an active role in projects that directly affect their lives, it encourages them to take ownership and responsibility of resources. It is critical to integrate public engagement strategies into planning processes and maintaining this in decision-making processes as projects mature toward construction and implementation phases (Kearnes & Motion, 2014).

8.2.2 Background

The removal of contaminants of emerging concern (CECs) was one of the key topics for discussions with the public, so that information is shared in an open forum. The public should gain an understanding of CECs, their lifecycle in the water system and methods used to destroy or remove them from wastewater. This also included tours of the laboratory facilities to understand the different analyses and routine monitoring that is undertaken to ensure safe consumption of reused water. Public perception of wastewater recycling in South Africa for DPR is highly variable due to the perceived health risk associated with the process.

Ilemobade, et al. (2009) conducted a Water Research Commission (WRC) study (Project No. K5/1701) and the key recommendations pertaining to public perceptions and awareness of water reuse are summarised below:

(i) If municipalities are considering supplying reused water to the communities, they first have to demonstrate competency and proven consistent supply of other services to increase public trust.
(ii) An integrated water reuse education/awareness programme would be beneficial for potential consumers to understand wastewater reuse. This programme can be enhanced using case studies of wastewater reuse in other communities.

Consumer acceptance of treated wastewater is influenced by factors like cost, ecological preservation, current water shortages, and anticipated water shortages. There seems to be more acceptance for industrial or agricultural purposes in some regions. There are countries that currently use reclaimed water. The Jebel Ali sewage treatment plant in Dubai, UAE: This plant uses membrane bioreactor (MBR) technology to treat wastewater to a high standard, producing recycled water that meets World Health Organization (WHO) guidelines for irrigation and landscaping uses. The Al Khumrah wastewater treatment plant in Jeddah, Saudi Arabia uses a combination of MBR and Reverse Osmosis technologies to treat wastewater to a high standard, producing recycled water that meets local standards for irrigation and industrial uses (Asaad & Suleiman, 2023).

However, countries like the Kingdom of Saudi Arabia are actively looking into reuse since the water usage of the country is high and groundwater resources are becoming scarce in addition to desalination being an expensive process. A study was conducted that surveyed 624 people. The general public's high literacy rate, coupled with intensive public awareness campaigns for behaviour change, as well as the capacity for detecting pollutants and germs in treated sewage effluent (TSE) are the key factors that play an important role in the success of the government's effort for large scale TSE adoption in the country. The study concluded that a substantial reduction in the country's reliance on costly desalinated water and fast depleting non-renewable groundwater requires complete reuse and recycling of treated wastewater for wider non-conventional purposes (Mu’azu, et al., 2020).

Sgroi et al. (2018) stated that a holistic approach, that takes into account all the water reuse factors (political, decisional, social, economic, technological and environmental) is needed for a sustainable water reuse implementation. A communication strategy report was undertaken by Slabbert & Green (2020) for water reuse in South Africa and the findings were as follows:

- The public require water reuse literacy.
- Education and communication were focus areas.
- This is a long-term project with no quick fix.

- Institutions such as Technical Vocational Education and Training (TVET) colleges are willing to educate the South African students by including specialised modules on water reuse to the appropriate qualifications

Based on the findings of these studies that were conducted, Darvill FERDP was able to use such knowledge to aid in their public acceptance agenda. Below are the aims for the public engagement plan for Darvill FERDP.

8.2.3 Aims

- To develop practical public acceptance strategies for a DPR plant that is aligned to national and international best practice.
- Ensure that the public understands the current water climate in South Africa, the need for water reuse and to address any misconceptions regarding the process and safety of DPR.
- To incorporate some of the institutional work and examples considered by Binz et al. 2016, and other studies discussed.
- Invite external stakeholders to the Darvill FERDP for site visits and to the annual National Forum to discuss reuse technology and operational issues.
- Gain the buy-in of the public and address their negative perceptions and concerns.
- Increase the water reuse network for the sector by establishing the KwaZulu-Natal (KZN) Water Reuse Chapter.

8.2.4 Methodology

- Define a scope for the public engagement – This should include why water reuse is important to South Africa and in particular the community that will be impacted.

- Identify the target stakeholders – Community and external stakeholder engagement entails several levels of education from young children, primary and secondary school groups, tertiary institutions and academics, the general public, community and political leaders, local and national government, various specialists, including visitors from outside KZN.

- Determine the level of engagement that is required (South African Legislative Sector, 2013):
    - Level 1 – “Inform” the public by providing them with balanced and objective information to assist them in understanding the problems, alternatives and/or solutions.
    - Level 2 – “Consult” where the public is invited to provide feedback, input or comment on analyses, alternatives and/or decisions.
    - Level 3 – “Involve” the public by providing them an opportunity for dialogue and interaction. This could also be described as direct public participation throughout the process to ensure that issues and concerns are consistently understood and considered.
    - Level 4 – Collaborate” which provides the public with the opportunity to partner or work jointly with decision-makers and the identification of the preferred solution.

The bulk water supplier is still ultimately the final decision maker.

- Methods of engagement:
    - Participatory methods – Active participation, advisory committees, citizens’ panels, focus groups, summits, community visioning and imagine workshops.
    - Consultative methods – Consultation, discussion groups, workshops, interviews, open days, polls, road shows, surveys and online forums.
    - Communication methods – Information sharing, advertising, websites, briefings, fact sheets, newsletters, media outreach and community meetings

- Online methods – Online engagement, online surveys, social media groups, community panels, online polls, Twitter chats, videos and slide shows (Kearnes & Motion, 2014)
- Plant tours, presentations and visual demonstrations for visitors in a classroom environment to be done by various uMngeni-uThukela Water specialists working on the project.
- Questionnaires and discussion forums to formulate acceptance strategies.
- A water reuse master class will be considered as one of the annual initiatives.

- Identify the time frame required for the public engagement; it often needs to be considered from conception through to design and implementation.
- Reporting and feedback – Reporting of the public participation events and results from any of the engagement methods must be recorded clearly and filed. Feedback must be shared with the relevant stakeholders, authorities and decision makers.
- Resources required – Finance (allocated budget), human resources, brand and marketing, infrastructure and information technology resources.
- Skills required – Those who are involved in public participation should also have detailed understanding of public participation practices, facilitation skills, project management skills, utilisation of social media platforms, conflict management skills, and skills for developing educational material (South African Legislative Sector, 2013).

8.2.5 Implementation

- Annual National Forums have successfully been held since 2019 where a diverse set of stakeholders were able to meet and disseminate information.
- Research collaborations were undertaken with Durban University of Technology, University of Pretoria, WRC, UKZN and the University of Birmingham.
- Site engagements were held with local government, public groups and a youth initiative.
- Pamphlets (Figure 8-17) and a video were produced to explain the process including the risks and areas of concern.
- Multiple presentations to stakeholders including South African Local Government Association (SALGA), Department of Water and Sanitation (DWS) and other water boards have been undertaken.
- Engagements with executive board members and project funders have also been held to gain buy-in. These included site tours as well as presentations.
- The National President Mr. Cyril Ramaphosa and the Minister of water and sanitation Mr. Senzo Mchunu (Figure 8-19) also visited the site on 21 July 2023 to officially open the treatment works. They toured the site and attended a presentation about the reuse work being conducted.
- Engagement and site visits with Suez Group and eThekwini Municipality has created a collaboration and partnership with UUW, for future training on reuse technology.

8.2.6 Outcomes

Multiple other projects have stemmed from the FERDP project through collaboration:

- Three subsidiary projects which also includes a circular economy project focusing on sludge reuse for composting.
- uMngeni-uThukela Water are also assessing reuse for non-potable purposes.
- Collaboration with City of Cape Town – Faure New Water Scheme.
- Collaboration with eThekwini Municipality and their reuse projects.
- KZN Chapter of the Water Reuse Division has been established through the Water Institute of South Africa (WISA).
- Articles such as "uMngeni-uThukela Water flagship project nears completion" have appeared in magazines by 3S media (Kelly, 2022), journals and media podcasts.

- Achieved buy-in from top management, financers and decision makers.
- A National Forum was hosted at the uMngeni-uThukela Water Visitor Centre at the Darvill FERDP on 26 November 2019 to bring together key industry stakeholders to discuss direct potable reuse, public perception and commence with the KZN Chapter of the WISA Water Reuse Division. The event was a success. Over 40 stakeholders attended and completed a questionnaire on water reclamation (see Appendix C) and Figure 8-1 to Figure 8-5 shows the results of the survey.
- National forums were also held in 2020 and 2021 at the WISA conference and a webinar, respectively. In 2020, the public perception questionnaire was modified and the results are shown below in Figure 8-6 to Figure 8-13.

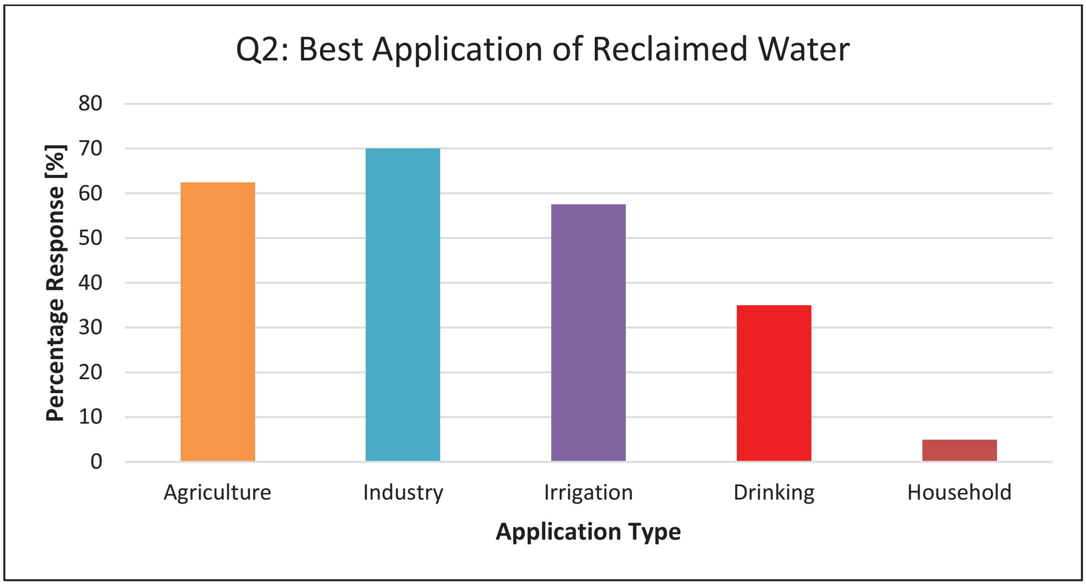

Figure 8-1: Responses for best application of reclaimed water

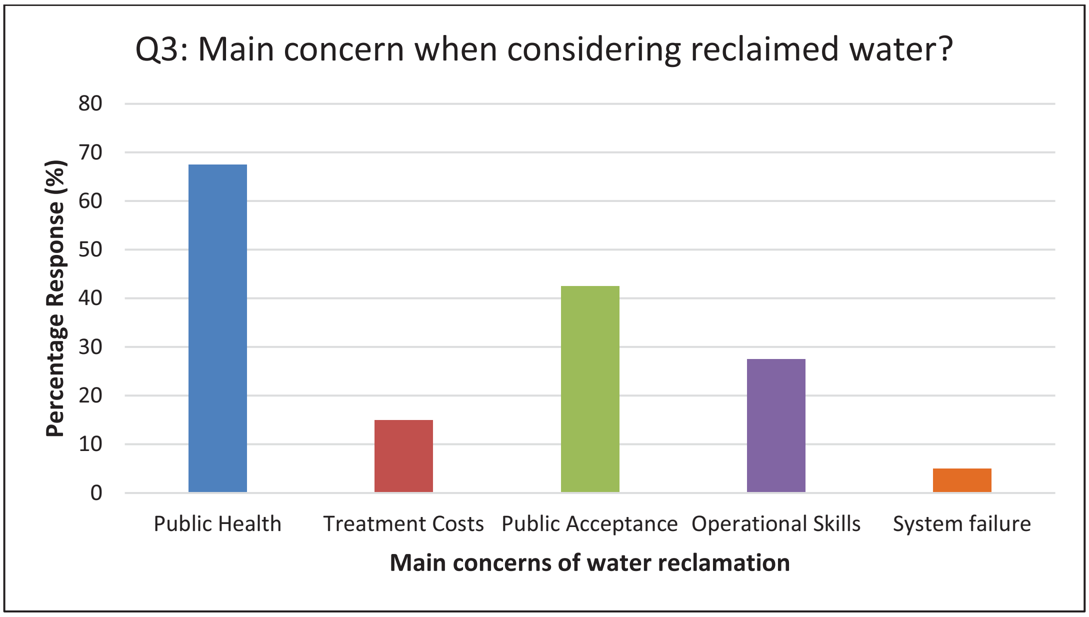

Figure 8-2: Responses to participants' concerns regarding reclaimed water

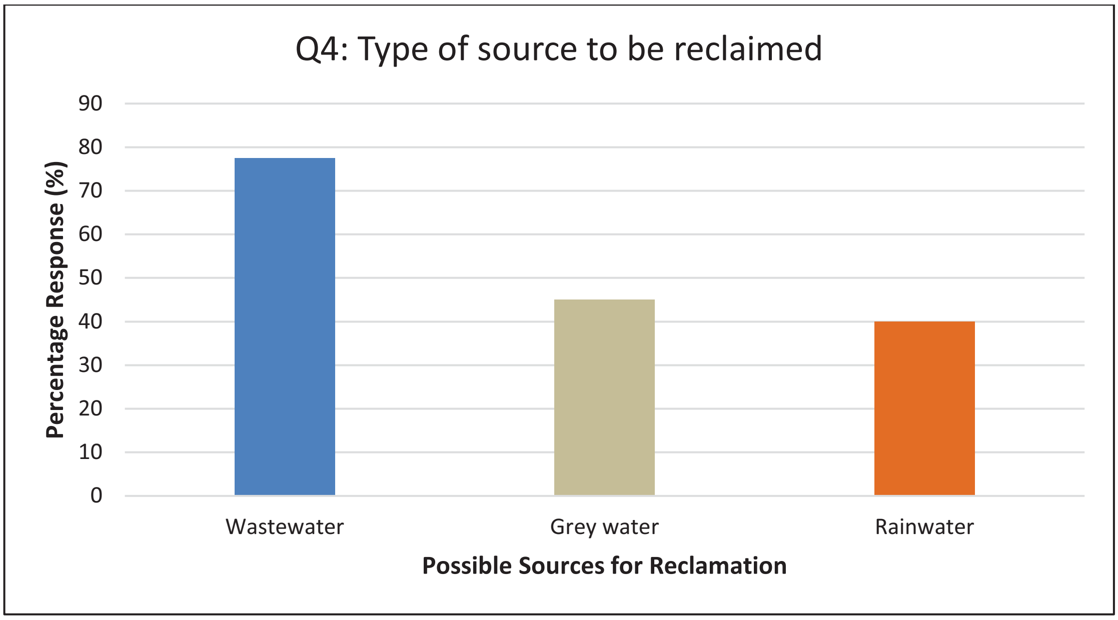

Figure 8-3: Results indicating the type of water that should be reclaimed during a drought

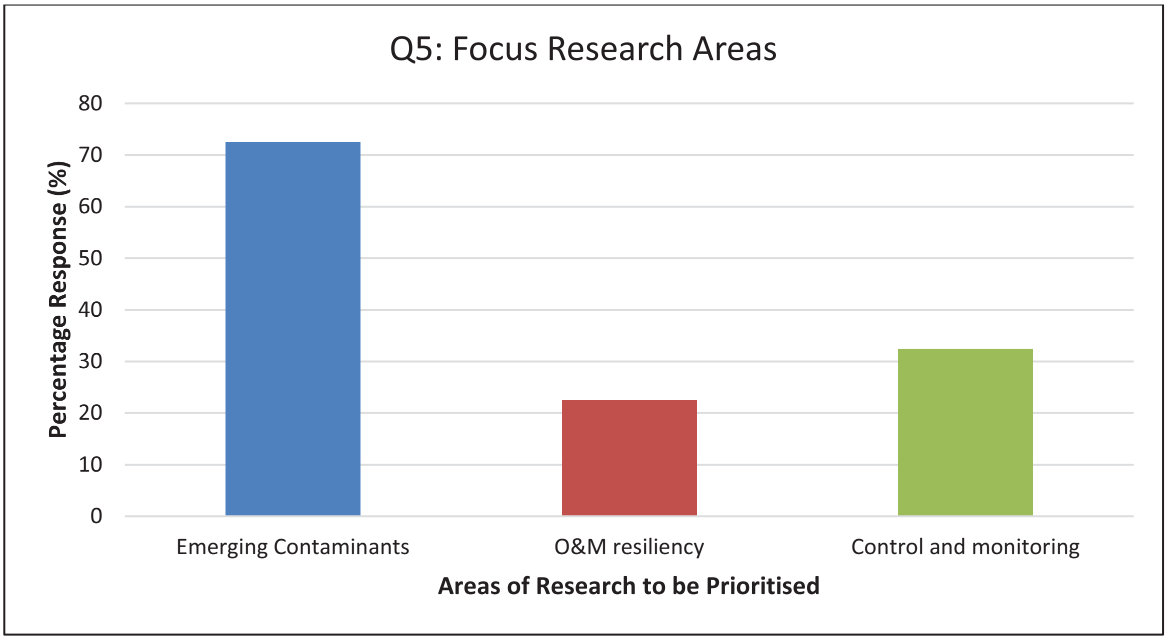

Figure 8-4: Response to the Research Areas that require prioritisation

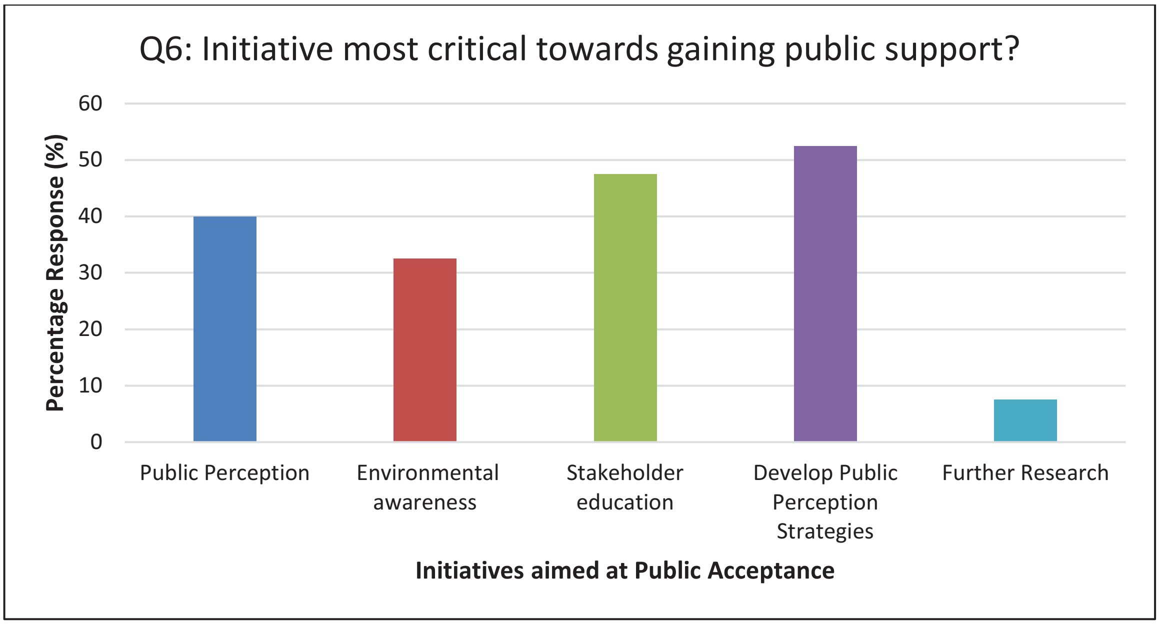

Figure 8-5: Results for the initiative that is most critical towards gaining public support

The questionnaire was designed to assess the understanding of reclamation, as well as provide guidance as to the application and future work in the field. The first question related to understanding the concept of reclaimed water, which had a 97.5% result. The results from the study show that under 40% of the participants were keen to treat reclaimed water for drinking and household use as shown in Figure 8-1. The main preference was towards applications of reclaimed water in industry and agriculture. A major area of concern was the public health and emerging contaminants as seen in Figure 8-2 and Figure 8-4, respectively, as emerging contaminants gained over 70% in the areas that require further research. This questionnaire assisted in understanding the different areas of concern that stakeholders have and where the focus areas should be in further research and studies. Figure 8-6 to 8-13 shows the results obtained from the 2020 National Forum Questionnaire.

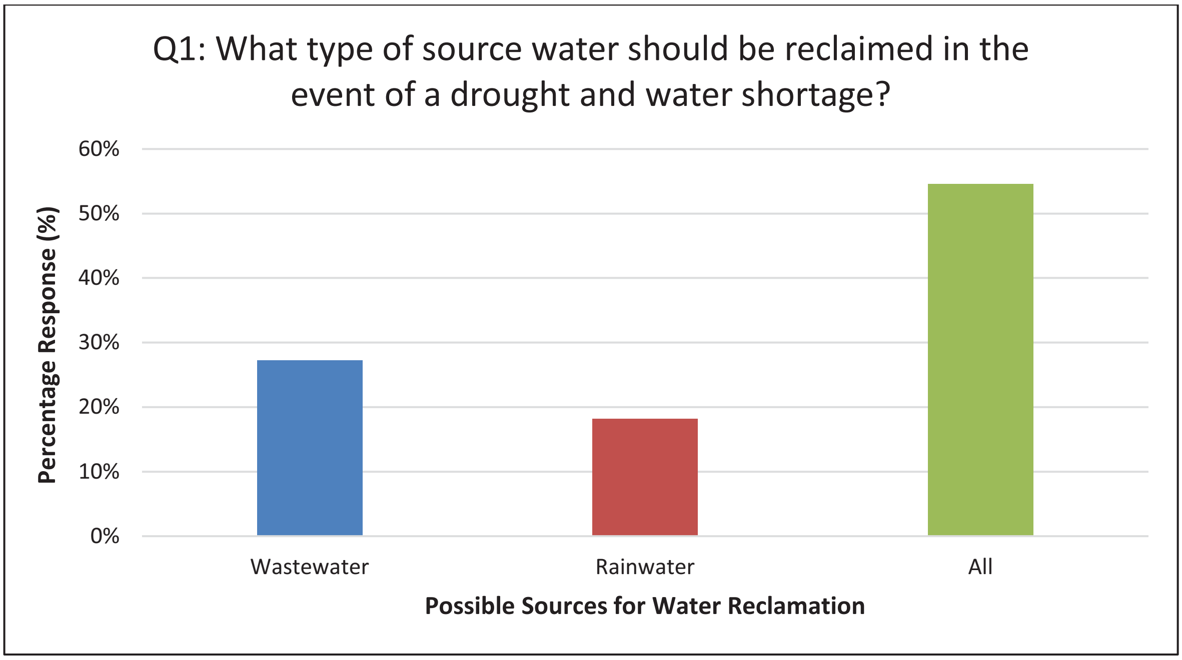

Figure 8-6: Responses to the type of source water for reclamation

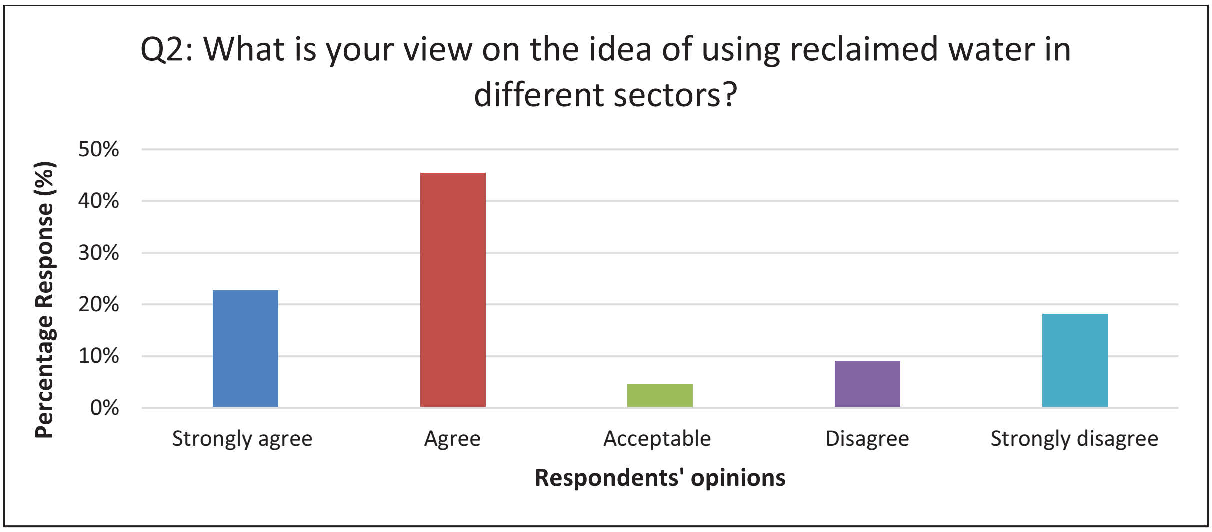

Figure 8-7: Results for the opinion of using reclaimed water in different sectors

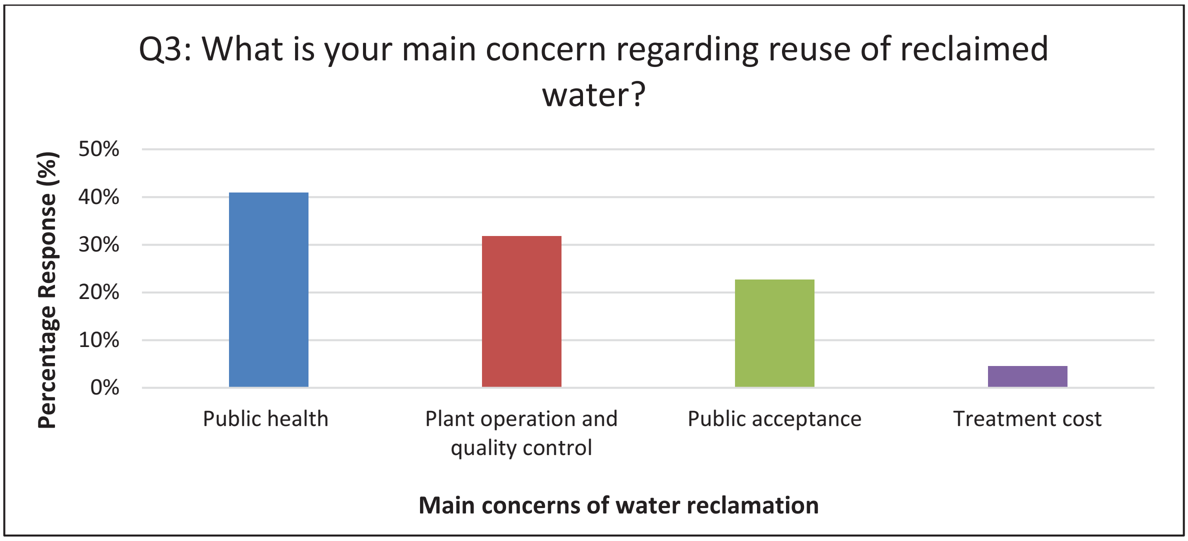

Figure 8-8: Main Concerns results with regards to usage of reclaimed water

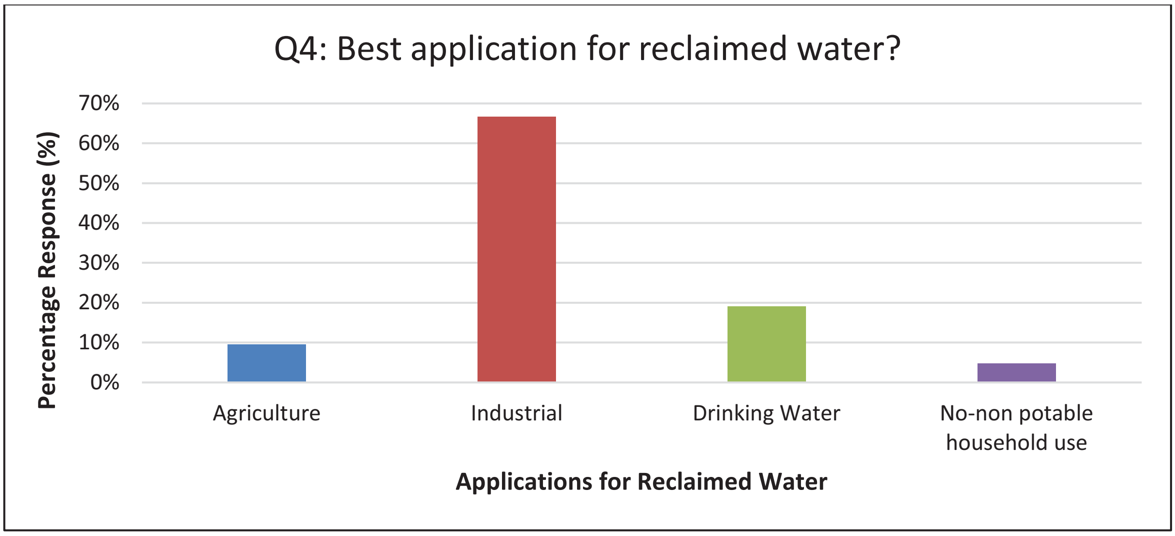

Figure 8-9: Respondents' idea of the best application for reclaimed water

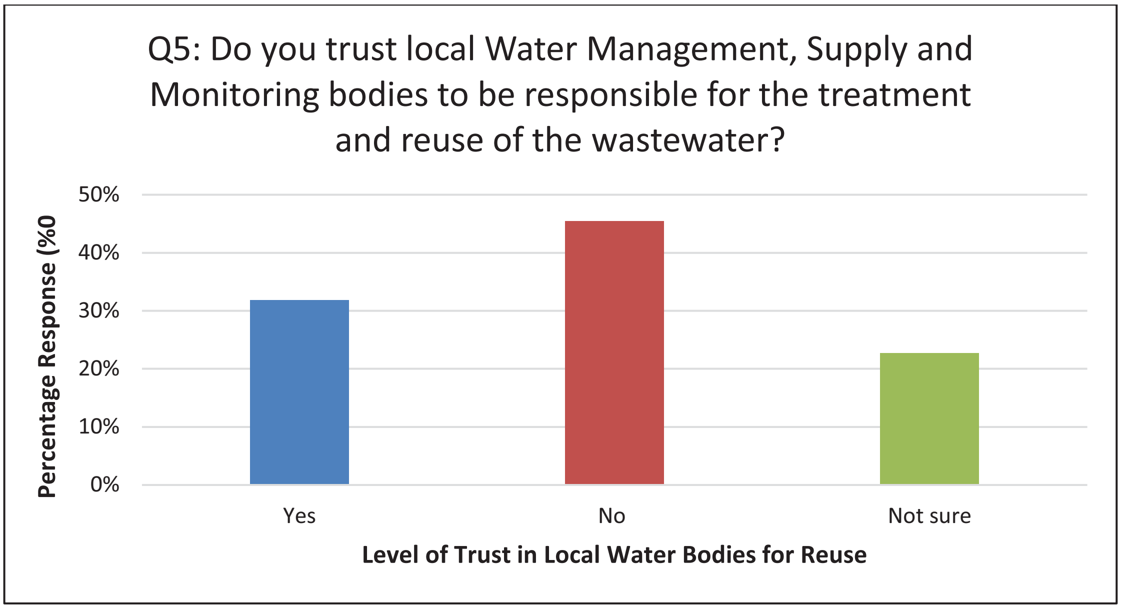

Figure 8-10: Results on the level of trust of local water bodies to be have responsibility of water reclamation

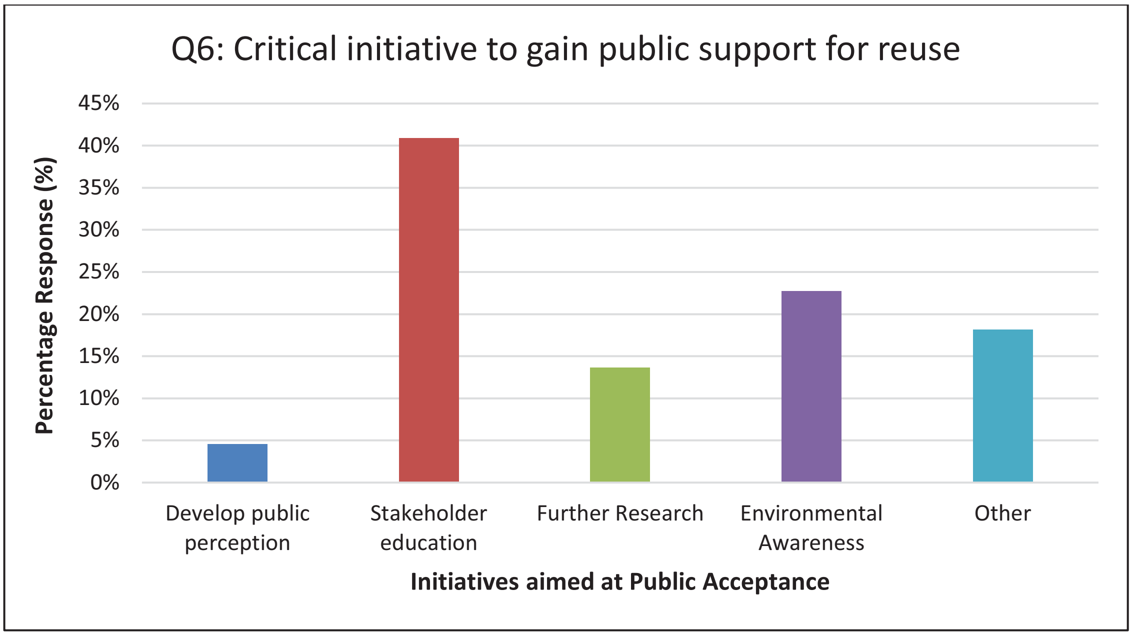

Figure 8-11: The initiatives that the respondents considered critical for Public Acceptance

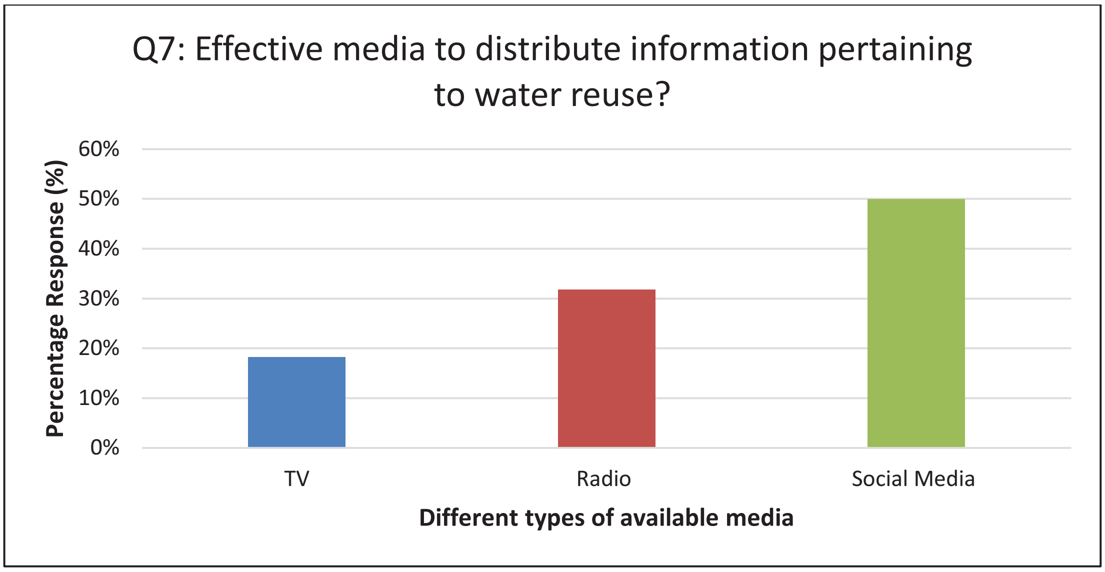

Figure 8-12: Selection of media for water reuse information distribution

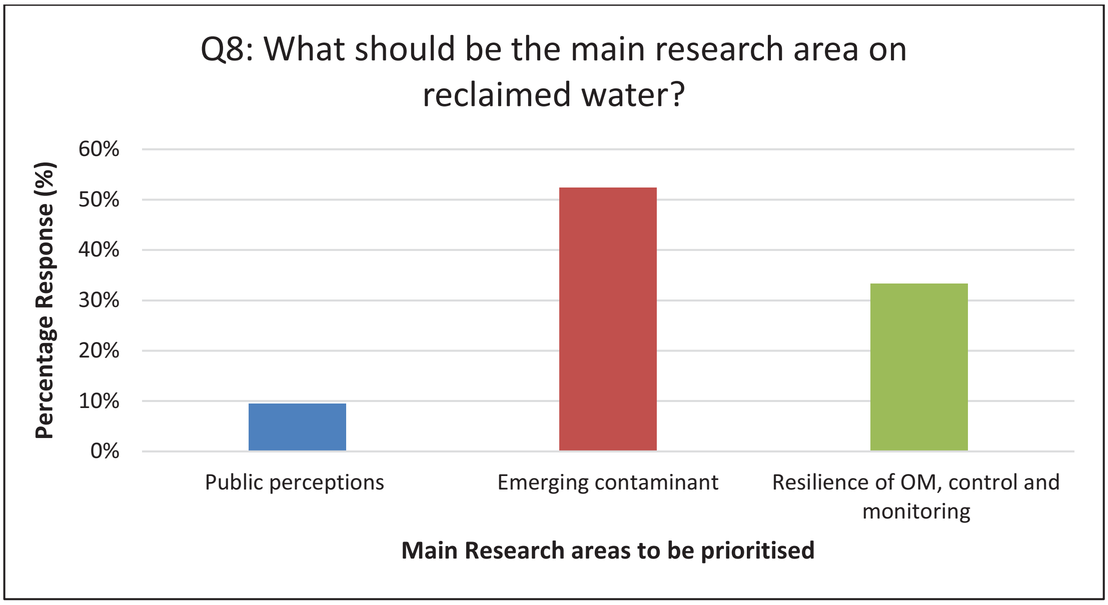

Figure 8-13: Focus areas for further research

In the 2020 results, 45% of the respondents agreed with the idea of using reclaimed water in different sectors (Figure 8-7) however, again it is shown that majority of the respondents (over 60%) were comfortable with the idea of reclaimed water being used in industry as compared to treating reclaimed water for drinking and household purposes as shown in Figure 8-9 . This implies that there is more to do in the area of public engagement regarding the acceptance of reclaimed water for drinking water purposes. Figure 8-12 shows that majority of the respondent's selected social media as the preferred method for information distribution. This could be due to the fact that there are many different social media platforms and they allow the public to directly engage in conversations. Emerging contaminants (Figure 8-13) also claimed the majority of responses for focus areas that require further and prioritised research in this survey as well.

8.2.7 Strategy for Advancement of Stakeholder Engagement

Water reuse is becoming increasingly vital as we seek sustainable solutions to address global water scarcity. Effective stakeholder engagement is essential to ensure the success and acceptance of water reuse initiatives. Table 8-1 shows some of the strategies for stakeholder engagement tailored to different focus areas.

Table 8-1: Strategies for Stakeholder Engagement in Various Focus Areas

Focus Area	Strategy
Business	Undertake core business well to ensure trust in services and trust in uMngeni-uThukela Water competence.
DWS	Assist with monitoring protocol and publish required data
Public Engagement	• Children can be educated through reading material, posters and exhibitions. • National forums and presentations to water professionals, academics, and various stakeholders. • Use of media platforms especially social media to gain the buy-in of those who are active on social media; uMngeni-uThukela Water has an active social media presence on Twitter, Instagram and Facebook and these platforms can be used to facilitate discussions around water reuse.
Marketing	Research journals, magazines and other forms of media.
Water and Wastewater Quality	Ensure that water and wastewater quality is always compliant according to SANS 241: 2015 for Drinking Water, general authorisations or licenses (wastewater) and uMngeni-uThukela Water internal standards.

Below are some of the photographs of the delegates that attended the public engagement initiatives hosted at the Darvill FERDP.

Figure 8-14: Social Media Engagement by UUW

Figure 8-15: The UUW operations team at the FERDP

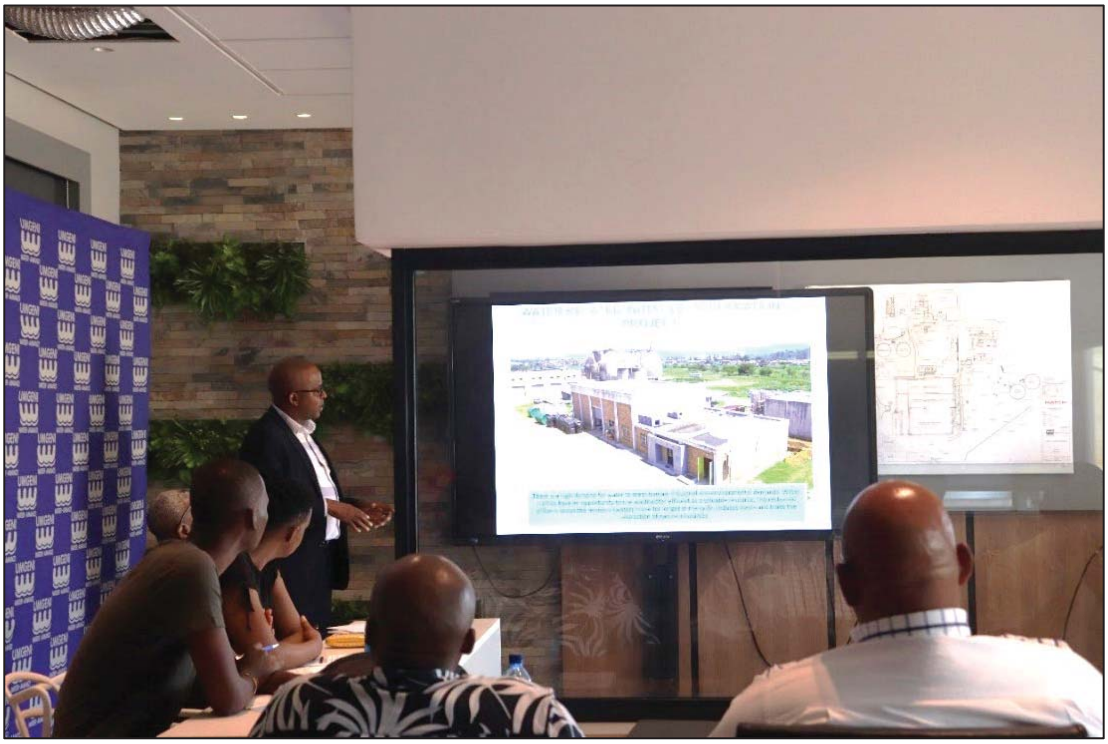

Figure 8-16: Presentation of the FERDP to the visitors

Figure 8-17: Pamphlets for the FERDP

Figure 8-18: The UUW team during a site visit with stakeholders

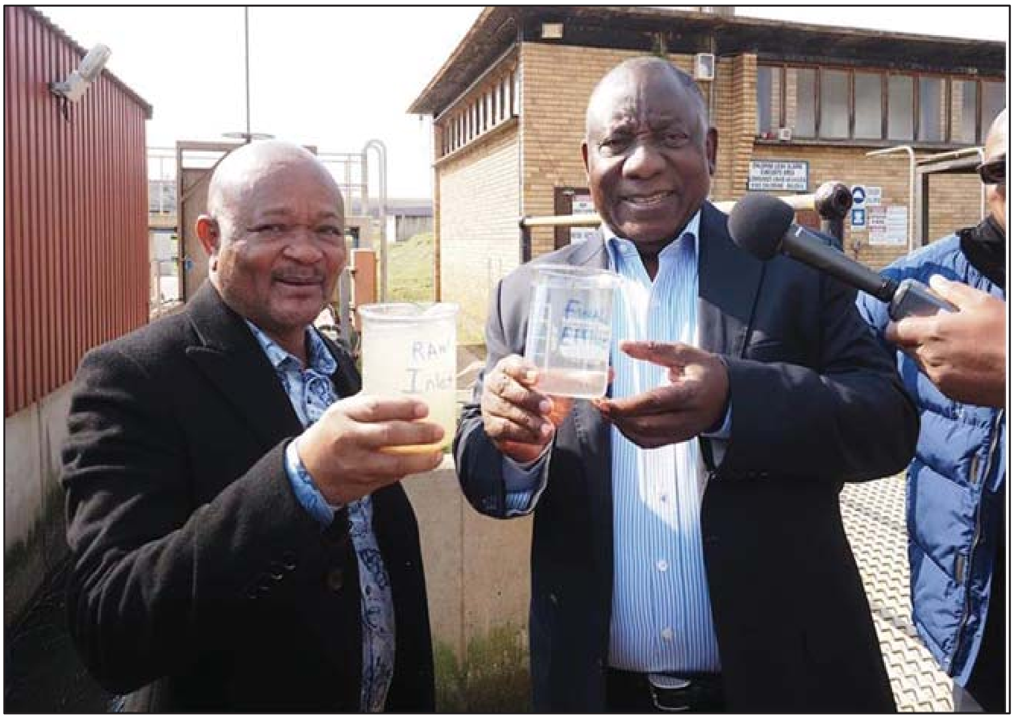

Figure 8-19: Minister of Water and Sanitation Mr Senzo Mchunu (left) and the National President Mr Cyril Ramaphosa (right) during their visit to Darvill FERDP

Figure 8-20: Process Engineer M. Schalkwyk presenting at the 13th IWA International Conference on Water Reclamation and Reuse

8.3 DISSEMINATION

8.3.1 Establishment of a co-funded research chair focusing on emerging contaminants

A meeting between various stakeholders, viz. Department of Science and Innovation (DSI), uMngeni-uThukela Water (UUW), National Research Foundation (NRF) and the University of Pretoria (UP) was held to explore the possibility of setting up a co-funded research chair at UP, to investigate issues on emerging contaminants in water with specific reference to water reuse, implications to the environment; and strategies/mechanisms to mitigate or avoid adverse impacts through proactive actions.

UP and UUW initiated a collaborative research partnership with the goal of understanding the implications of three emerging classes of chemicals (engineered nanomaterials, antibacterials widely used in personal care products, and antiretroviral drugs with specific focus to active ingredients used for HIV therapy). The research considered both short and long-term mechanisms that can support effective management of these emerging contaminants in WWTWs and water treatment works (WTWs). The choice of these chemicals was informed by the lack of their inclusion currently in the South African environmental laws. As such, these chemicals are not monitored, have no set removal standard thresholds from WWTWs or WTWs, their likely impairment to ecological health remain un-quantified, and their implications to the human health through deterioration of drinking water quality remains unknown.

For these reasons, the UP/UUW partnership seeks to develop human capacity that can effectively manage these contaminants especially with increasing demand for wastewater reuse, exacerbated by diminishing freshwater sources due to drivers linked to climate change. Capacity building activities include staff at UUW working towards masters and doctoral degrees at UP. The research programme was fully supported by DSI and NRF (South African Research Chair Initiative, SARChI) and co-funded by UUW (R500 000 per annum). The co-funding Memorandum of Agreement (MOA) and concept document was drafted and submitted to the NRF for finalisation and sign-off. The co-funded SARChI Chair: Water and Environment was appointed in 2020.

uMngeni-uThukela Water staff has also presented the water reuse initiatives at national and international conferences.
National Conferences:

- A poster presentation was accepted for WISA Biennial Conference 2020:
- Maharaj, L., Toolsee, N., Thompson, P. “Establishing a co-funded research chair focusing on emerging contaminants”, Water Institute of Southern Africa (WISA) 2020 Conference, #allhandsondeck, 31 May-4 June 2020, Johannesburg.
- An oral presentation was accepted for the WISA 2020 Water Reuse Workshop:
- Maharaj, L., Schalkwyk, M., Mnguni, M., Metcalf, G. “Feedback on National Forum: A demonstration of treatment technologies for direct reclamation”, Water Institute of Southern Africa (WISA) 2020 Conference, #allhandsondeck, 31 May-4 June 2020, Johannesburg.

International Conferences:

- A paper and poster were presented at the International Water Association (IWA) 12th International Conference on Water Reclamation and Reuse in Berlin, Germany from 16 to 20 June 2019. Three UUW staff attended the conference.
- Maharaj, L., Schalkwyk, M., Mnguni M. “Establishment of a national learning platform for direct potable reuse in South Africa” (Oral Presentation).
- Thoola, M., Mazibuko, S., Maharaj, L. “Do conventional wastewater processes remove emerging contaminants for water reuse purposes” (Poster Presentation).

- A presentation was also done at the IWA 13th International Conference on Water Reclamation and Reuse in Chennai, India from 15 to 19 January 2023. Two UUW staff attended the conference.

- Schalkwyk, M., Getahun, S., "Comparing the Removal Efficiency of Conventional Direct Potable Reuse Technology with the Removal Efficiency of Biotechnology" (Oral Presentation).

8.3.2 Further Research and Technology Initiatives

Several piloting initiatives on new technologies for pharmaceutical and pesticides removal are in the process of being discussed with the University of Birmingham (UoB) and other international specialist technology suppliers. UUW and UoB have signed a nondisclosure agreement and there is a possibility of sourcing funding for this initiative via the United Kingdom Research Council with UUW as a partner.

A postdoctoral research fellow, Dr. Samuel Getahun, was recruited via UKZN WASH R&D Centre (formerly Pollution Research Group) with Prof. C Buckley as his UKZN supervisor and M Schalkwyk as his UUW supervisor, to support the WRC project. The latest initiative is also aimed at partnering in this research with University of Zululand (UNIZULU) research academics.

Capacity Building:

- WRC Support grant funding was approved for a project in the School of Chemistry, UKZN, supervised by Dr. Gumbi. The student has registered in 2019 and work is on-going.
- Two additional support grants are in the process of being finalised for UKZN.
- Two UP postgraduate (M.Sc.) students, S Mazibuko and M Thoola completed their studies on engineered nanomaterials projects supervised by Prof. Musee.
- uMngeni-uThukela Water's technicians, graduate and in-service trainees have been trained to operate the FERDP.
- There are also three post-graduate students from UKZN who are being supported through K5/2807//03.
  - Sanele Mthembu (Ph. D. candidate) working on "Role of Green Technology in Recycling Concentrated Brine Water Resulting From Water Treatment Plants",
  - Lungile Hadebe (MSc candidate) whose project is on "Sustainable Porous Carbon Electrode Material Derived From Coffee Waste Grounds For Utilization In Capacity Deionisation" and
  - "Development Of An Analytical Method For Monitoring Of Engineered Nanomaterials For Wastewater Reclamation" done by M. Sc. candidate Nokwanda Hendricks.
- uMngeni-uThukela Water has also supported a postgraduate study from 2021 to 2023, *"Analysis of Selected Pharmaceuticals and Metabolites at Darvill Wastewater Treatment Plant in KwaZulu-Natal"* by Nikitha Inarmal and Prof. Brenda Moodley, School of Chemistry and Physics, UKZN.

CHAPTER 9: CONCLUSIONS, LESSONS LEARNT AND RECOMMENDATIONS

9.1 CONCLUSIONS

This project explored the technical viability of using multi-barrier treatment processes to treat the final effluent from Darvill WWTW into potable water using configuration one, where a conventional treatment (HP Wash) plant is followed by advanced oxidation process (AOP), granular activated carbon (GAC), ultrafiltration (UF) and disinfection. It also addresses various challenges encountered during the installation, commissioning, and operation of the plant.

9.1.1 Development of a Water Reuse Safety Plan (WRSP)

The WRSP was key in defining water quality monitoring program and establishing a baseline to assess technology effectiveness (performance evaluation), removal of microbiological water quality determinants as well as CECs, thus contributing to the project's primary aim. The plan developed represents a proactive approach to ensuring the safe and sustainable operation of the water reuse treatment system. It assessed potential hazards, identified key risk factors, and helped implement control measures to mitigate risks to the environment and public health. By targeting CECs and continuously monitoring treatment performance, the reuse plant was able to meet water quality regulatory standards. The implementation of effective management and communication strategies as per the plan, along with a dedicated commitment of the WRSP team to continual review and enhancement, plays a crucial role in the success of this plan.

9.1.2 Installation and Commissioning

In the implementation (installation, commissioning, operations and maintenance) of the DPR several challenges were identified and addressed, contributing to the secondary project aim. During installation and commissioning, quality assurance played a vital part in the construction, manufacturing, installation and testing of the systems and individual equipment were conducted according to the specific quality standards. Quality control plans were in place to ensure that all specifications were noted and inspections and testing results met the required acceptance criteria. The project faced many challenges with the major ones being external factors that contributed to the delays in the installation and commissioning of the FERDP which included COVID-19 ramifications and change of main contractors. During the construction phase, some modifications had to be made to the project scope due to challenges such as material unavailability and delays occurred as a result of downturn of the construction industry. Loadshedding was a major factor which caused delays during commissioning as well as loss of production during operations. Since the electricity crisis in South Africa is ongoing, loadshedding schedules often change regularly hence planning for production requirements is important. The four stages of commissioning were implemented, albeit there was some overlap due to the delays experienced and deadlines. Some of the snags such as undersized feed pumps for the GAC filters, resulted in the filters being offline hence, causing interruptions in full performance testing.

9.1.3 Operation and Maintenance

Water reuse is relatively new in the South African context and the FERDP experience provided the opportunity for the bulk water supplier to acquire experience operating a DPR plant. An operational and maintenance protocol was developed from the experience of operating the FERDP which can be used by other municipalities and water suppliers that wish to implement a similar plant. It was noted that operators should have experience operating water and wastewater treatment plants and need additional training for operating advanced treatment technologies. Operators also require possess effective communication skills, data recording skills and be computer literate, amongst other competencies. Safety training is an important component of operation since chemicals such as ozone, citric acid, sulphuric acid and hydrogen peroxide are not used on conventional water treatment plants and require careful handling to avoid dangerous exposure or injury to plant personnel. Maintenance of the FERDP ensures that the plant will operate efficiently and preserve the life of the equipment. Planned maintenance on common equipment such as pumps, mixers, air blowers and compressors can be done by the plant maintenance team. Complex units such as the ozone generator and ultrafiltration unit requires a technician with specialised expertise, such as the supplier, for maintenance and repairs.

9.1.4 Public Engagement and Knowledge Dissemination

Public participation was an important part of the project to address the concerns and perceptions associated with direct potable reuse. The activities comprised of presentations at National Forums, national and international conferences, plant tours, demonstrations, questionnaires and site engagements with many different stakeholders at all levels. This was successful as the buy-in was obtained from the various stakeholders and collaborative projects with other municipalities and academic institutions have stemmed from the FERDP project. Capacity building was also a significant component of knowledge dissemination and this was done by supporting postgraduate students with studies related to the water and wastewater industry and training of UUW technicians, graduate and in-service trainees to operate the FERDP. Finally, a public engagement protocol was developed to provide guidance to any entity that plans to implement direct potable reuse. The protocol will be revised regularly for a high-quality engagement and inclusiveness and demographic diversity with the participation of stakeholders.

9.2 LESSONS LEARNT

9.2.1 Commissioning and Operational Lessons Learnt:

- **Design and installation:** Changes made to the tenders were to mitigate project delays, save cost and ensure that the project could use local content, as in the case of the valves. This sort of value engineering is required before the tender is out, as this will prevent variation orders and later delays. Front-end loaded projects are easier to manage as essential things such as proper ventilation in the chlorine room would be found earlier and included in the bill of quantities.
- **Prioritising Communication:** It is important to prioritise communication between all parties involved (commissioning team, engineer and contractors) to ensure that there are no knowledge gaps in regarding the activities on the plant.
- **Specific Contracts:** Contracts must be specific and clearly state the custodianship of equipment and boundaries of work. Technicians: A local technician is best suited for the training and commissioning as well as to address any issues that arise especially for “black box” systems such as the ozone generator. Currently, the team has to await a technician from the supplier to come to the province to troubleshoot issues with the ozone generator unit which results in delays for full operation of the FERDP.

- Training:
  - Operator training must be conducted before the full plant operation and every operator should be aware of respective specific duties that need to be carried out and procedures for new tests such as the ozone residual testing. Training that is completed prior to plant operation will ensure that all relevant staff members will be trained and have exposure to familiarise themselves with the equipment and processes.

- Training on the ozone system must be detailed and comprehensive so that the staff working with the system has the knowledge and confidence to operate the plant. Handheld ozone detectors are also advised to ensure that leaks can be identified immediately. There is also confusion between an ozone leak versus the residual ozone odour hence these must be addressed with staff clearly as well as the methods to deal with such leaks.

- **Asset Management:** The plant asset and maintenance team need to be more involved in the commissioning process especially regarding troubleshooting as there is a gap in knowledge since they are not fully involved. Maintenance training should also be thoroughly done with the plant team by the contractors and equipment manufacturers so that they understand each process equipment and the engineering discipline that is in charge of the different equipment.

9.2.2 Planned maintenance (PM):

- PM is of the utmost importance. Maintenance and servicing for equipment that requires external contractors must be adequately scheduled since delays results in downtime and loss of production.
- Response time from onsite maintenance staff should be prompt and communication regarding delays must be made clear. Poor response time especially for uncomplicated checks and repairs results in unnecessary downtime.
- Servicing and calibration as well as availability of standby meters should be a priority if the system is to operate uninterrupted.
- Scheduling of work to be done by contractors as well as onsite staff should be properly planned especially during the December/January period as many companies close for the festive season and staff members apply for vacation days. This often leaves the plant understaffed or unit processes offline for long periods of time since it cannot be attended to by contractors.

- Plant Design:
  - The design of new plants should accommodate for common areas such as a kitchen, sufficient working areas with internet and network cables, electricity plug points and laboratory space if tests are to be conducted onsite.
  - Accessibility needs to be accounted for in the design. It was noted that access to the influent chamber was difficult since there was no fixed ladder initially installed and the inlet valves could only be accessed inside the chamber which also poses a safety hazard.

- CECs Analysis:
  - Many of the laboratories in South Africa only have the capabilities to analyse a specific number of CECs. It is advisable to liaise with different laboratories regarding the CECs they can analyse and if these would be appropriate for the plant operation and study. If further CECs need to be analysed, there should be pre-agreements in place if using overseas laboratories as well as to have the logistics in order before the actual plant operation commences.
  - When testing CECS for research purposes, universities and other laboratories that are not accredited but have Quality Control methods in place can also be used.
  - It is important to develop in-house analytical methods and capability to enhance the precision of results and minimize dependency on external laboratories.

- Operations:
  - Shift teams require planning and should have sufficient staff and be organised in advance to accommodate for planning of the shift roster and any emergency situations where a standby operator is required.

- Record keeping for plant log sheets, log books and issues arising during operation as well as any work done by contractors should be legibly noted and kept safely. These records should also be referred to by operators when shift handovers are done. They should be recorded both on paper and computer.
- Stock of chemicals onsite must be noted weekly as well as the expiry dates so that they can be procured before the current chemicals are depleted.
- O&M manuals and FDS documents need to be finalised, approved and made available before the plant can be operated to ensure that a guide is available to the staff for operation and troubleshooting purposes.

- **Safety:** A safe working environment is important and must be taken into account and budget allocated for security services especially at night in areas such as the FERDP where it is poorly lit and isolated from majority of the main plant (Darvill WWTW).

- Ozone:
    - A local technician is best suitable for the commissioning and training of operators for the ozone system. Since the ozone unit in the water treatment works was procured from overseas and the site technicians were not experienced with the technology, a technician from overseas was brought in to assist with the start-up and operation. This causes delays as well as if problems occur at a later stage, local technicians will be able to respond to site issues much faster than an international consultant.
    - The SCADA system and interlocks must be robust, and alarms must be attended to immediately.
    - Ozone gas sensors must be checked and maintained frequently (usually it requires replacement every 6 months)
    - All critical signals must be logged and trended; generator run signal, cooling water run signal, pressures and set points. This will help to determine the frequency of any faults and potentially the cause of the fault by looking at other trended data.
- UF system:
    - The spent chemicals used for the clean-in-place (CIP) for the UF is disposed to the balancing tank that feeds the reactors at Darvill WWTP. Some of the consequences can include disruption of the microbial community in the reactors and changing of the conditions such as pH, temperature, sulphur content amongst others. Sludge can also be affected by the chemicals as well as the treated effluent which may affect the environment it is being discharged to and affect the compliance standards.
    - UF systems in other industries usually neutralize the spent chemicals to a non-hazardous form for disposal such as pharmaceutical industries or they may be collected in a safe and controlled manner or treated and disposed as hazardous waste according to strict regulations.
    - All safety protocols must be followed and personal protective equipment (PPE) to be worn when handling chemicals used for the backwash processes. Any acid to be discharged should be neutralised. There should be a SCADA pop-up for draining the tank that asks if the chemicals have been neutralised before opening the drain valve. This will prevent any risk of injury to personnel and any damage to the equipment on the plant.
    - Standard Operating Procedures (SOPs) for the different modes of UF operations must be developed by the technicians/operators who will be working on the plant to ensure ease and accuracy of operation. Valves and pipelines must be labelled, and the SOP should reference these correct labels. The SOPs should be easily accessible and available onsite during operation.
    - Interlocks and alarms for the system must be robust. The UF equipment is sensitive and expensive hence, any malfunction that requires replacement of parts can mean procurement procedures must be followed if there are no spares available onsite or locally which will delay the project. Alarms need to have a sound so that the operators will know there is an issue

and address it. On large plants, alarms can sometimes be silent although visible, but this can result in the alarm going off unnoticed or being ignored.

- If a system is developed for research purposes, where process streams are compared it is recommended that there are dedicated UF membranes per stream or membranes to be changed before testing. This will ensure that the results are comparable by starting each configuration with new membranes and there is no risk of using a membrane that may have developed a biofilm over time.

9.3 RECOMMENDATIONS

Although the project has demonstrated the effectiveness of using these treatment technologies for DPR, there is still a need for further research and development in the field. DPR demonstration plants provide a unique opportunity to test and evaluate advanced water treatment technologies and processes. The following are some recommendations for future work and research at the Darvill FERDP:

1. Full scale plant: if the plant determinands do not meet SANS 241:2015 standards, it should be diverted back to plant. i.e. – if alert level exceeds plant design parameters, the plant design should include a diversion point.
2. Water Reuse Safety Plan (WRSP): The current WRSP, developed by the UUW team, could benefit from involving external stakeholders like regulatory authorities, and the public. Their inclusion would provide additional perspectives and strengthen the WRSP.
3. Comprehensive CEC detection and monitoring: Explore the presence and levels of CECs across various environmental conditions, including seasonal variations and weather patterns. Expand the existing list of targeted CECs to encompass a wider range of pharmaceuticals and other emerging contaminants such as Disinfection Byproducts (DBPs), Transformation products, microplastics, hormones and pesticides to provide a more comprehensive understanding of the contamination landscape. It is also important to develop in-house analytical methods to enhance the precision and dependability of data.
4. Investment into equipment and training for CECs analysis must be prioritised throughout the country's laboratories and universities to accommodate for scaling up and implementation of the reuse plant at a nationwide level.
5. Operations: The operators must be trained to fully operate the ATP and troubleshoot any operational issues that could occur that would not require assistance from the asset management team. Operators along with the process technicians and process engineers should study the advanced water treatment courses that are offered by overseas institutions or courses that will be developed in the country in the near future. These courses include advanced water treatment processes and membrane technology and applications in the water and wastewater industry. Attendance of seminars and conferences such as WISA is also important to constantly keep abreast of the changes and advancements in the water reuse sector.
6. Maintenance: Local technicians from asset management should be trained at an expert level for the advanced treatment plant for trouble shooting and minor servicing. Service contracts and Service Level Agreements (SLAs) can be approved for external contractors and technicians for work that includes major services, breakdowns and repairs. It is also advisable to have a panel of technical experts at experts at hand (also done through SLAs) who can assist with future projects and the continuation of the reuse project.
7. Monitoring and control systems: DPR demonstration plants require sophisticated monitoring and control systems to ensure the effective operation of the treatment process. This demonstration plant can be used to evaluate and demonstrate the effectiveness of different monitoring and control systems, such as real-time monitoring and automated control, as well as artificial intelligence (AI) in optimising the treatment process and reducing operating costs.

8. Regulatory framework: Develop and implement regulatory frameworks for the safe and effective implementation of DPR.
9. Public acceptance and perception: It is recommended to undertake research that is focused on conducting surveys and focus groups with members of the public to assess their knowledge, attitudes, and beliefs about water reuse and to identify potential barriers and concerns that may need to be addressed to increase public acceptance.
10. Presently, the exchange of information among water reuse initiatives and projects in South Africa are limited. It is advisable to create a collaborative communication platform that facilitates the sharing experiences and knowledge among them. This platform should aim to synchronize their objectives with the goals of the national program, ensuring a unified and effective approach to water reuse.

In general, this project has shown that the determinants current multi-barrier process configuration produced standard-quality drinking water from treated wastewater. However, there is a clear opportunity to enhance the plant's overall performance by pursuing further optimization measures, investing in human resource development and fostering consistent public engagement to elevate improve acceptance and fully harness its potential. The South African water reuse sector still in its early stages of development, but it is expected to grow in importance as the country faces increasing water scarcity challenges.

It is therefore recommended that the WRC and the utility companies such as UUW, in collaboration with other relevant organizations in South Africa and globally, continue their collaborative efforts. These efforts should focus on improving the quality of treated wastewater, advancing the adoption of water reuse across diverse sectors, and actively exploring innovative approaches to water reuse to address the evolving water scarcity challenges.

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APPENDICES

APPENDIX A: WATER REUSE SAFETY PLAN FOR DARVILL FERDP

WRC K5-2807 Water Reuse Safety Plan for

APPENDIX B: COMMISSIONING

ITEM NO	DESCRIPTION	ACCEPTANCE CRITERIA	CERTIFICATION	TO BE INCLUDED IN DATA BOOK	CONTROL ACTIVITIES: HOLD or WITNESS BY 1	2	3	4	INSPECTION REQUIRED: VIS	DIM	DOC	CERT
1	DESIGN REVIEW											
1.1	Drawing Approval	PD5500 : 2015 Cat.2	DRAWING	YES	H		√	H			X	
1.2	Design Calculations	PD5500 : 2015 Cat.2	DESIGN DATA SHEET	YES	H		H	H			X	
1.3	Weld Procedure Specification	EN ISO 15609-1	WPS	YES	V		R	R			X	
1.4	Welder Procedure Qualification Record	EN ISO 15614-1	WPQR	YES	V		R				X	X
1.5	Radiographic Testing Procedure	PD5500 : 2015 Cat.2	OSG	YES	V		R				X	
1.6	Dye Penetrant Procedure	PD5500 : 2015 Cat.2	REPORT	YES	V		R				X	
1.7	Pickling & Passivating Procedure	LEA-Q005	REPORT	YES	V		R				X	
1.8	Pressure Test Procedure	PD5500 : 2015 Cat.2	AVCO	YES	V		R	R			X	
2	TOP DISH											
2.1	Material identification	DRAWING	MILL CERTS	YES	V	V	√	R				X
2.2	Mark out & cut segments	DRAWING			S	H	-		X	X		
2.3	Send for forming	LEA-Q001			S	S	-		X	X		
2.4	Dimensional Check	DRAWING			V	H	√		X	X		
3	Bottom Dish											
3.1	Material identification	DRAWING	MILL CERTS	YES	V	V	√	R				X
3.2	Mark out & cut segments	DRAWING			S	H	-		X	X		
3.8	Send for forming	LEA-Q001			S	S	-		X	X		
3.9	Dimensional Check	DRAWING			V	H	√		X	X		
4	Distribution Plate											
4.1	Material identification	DRAWING	MILL CERTS	YES	V	V	√	R				X
4.2	Laser Profiling	DRAWING			S	H	-		X	X		
4.3	Dimensional Check				S	S	√		X	X		
5	SHELL											
5.1	Material identification	DRAWING	MILL CERTS	YES	V	V	√	R				X
5.2	Mark & cut	DRAWING			S	H	-		X	X		
5.3	Join long seam	WPS			S	S	V					
5.4	Check fit up				S	S	S		X	X		
5.5	Weld Long Seam	WPS			S	S	√		X			
5.6	Grind Inside & Outside Weld Flush				S	S	S		X			
5.7	Dye Pen Weld (100%)	LEA-Q003/LEA-Q002	REPORT	YES	S	S	√	R	X		X	
6	NOZZLES AND PIPING											
6.1	Material identification	DRAWING	MILL CERTS	YES	V	V	√	R				X
6.2	Mark & cut material	DRAWING			S	S	-		X			
6.3	Machine flanges	DRAWING			V	V	S		X	X		
6.4	Cut pipes	DRAWING			S	S	S		X	X		
7	LEGS											
7.1	Material identification	DRAWING			S	S	√	R	X			
7.2	Mark plates	DRAWING			S	S	S		X			
7.3	Cut and bend plates				S	S	S		X			
7.4	Weld	WPS			S	S	√		X			
8	ASSEMBLING OF SHELL											
8.1	Join Top Dish end to shell	DRAWING			S	S	√		X			
8.2	Check Fit up				S	S	S		X			
8.3	Weld (Double Tig)	WPS			S	S	S		X			
8.4	Grind Inside Flush				S	S	S		X			
8.5	Dye Pen Weld	LEA-Q003/LEA-Q002	REPORT	YES	S	S	√	R	X		X	
8.6	X-ray (100%)	PD5500 : 2015 Cat.2	REPORT	YES	H	H	H/√	R	X		X	
8.7	Join bottom dish end to shell	DRAWING			S	S	S		X			
8.8	Check Fit up				S	S	S		X			
8.9	Weld (Double Tig)	WPS			S	S	S		X			
8.10	Grind outside & Inside Flush				S	S	S		X			
8.11	Dye Pen Weld (100%)	LEA-Q003/LEA-Q002	REPORT	YES	H	H	√				X	
8.12	X-ray (100%)	PD5500 : 2015 Cat.2	REPORT	YES	H	H	√	R	X		X	
8.13	Fit Nozzles to vessel	DRAWING			S	S	S		X			
8.14	Check fit up				S	S	S		X			
8.15	Weld	WPS			S	S	√		X			
8.16	Dye pen welds (100%)	LEA-Q002	REPORT	YES	S	S	√	R	X		X	
8.17	Assemble legs on to Shell	DRAWING			S	S	S		X			
8.18	Check fit up				S	S	S		X			
8.19	Weld	WPS			S	S	√		X			
8.20	Dye pen welds (100%)	LEA-Q003/LEA-Q002	REPORT	YES	S	S	√	R	X		X	
9	Final											
9.1	Dimensional Check				S	S	H		X			
9.1	Final Clean				S	S	V		X			
10.1	Hydro test	LEA-Q009	REPORT	YES	H	H	H/W	W	X			
8.21	Pickle & Passivate	LEA-Q004/LEA-Q005		YES	H	H	V		X		X	
10	FINAL INSPECTION											
10.2	Internal inspection				H	H	W		X			
10.3	External inspection				H	H	W		X			
10.4	Stamp Nameplate & fit	DRAWING		YES	H	H	√	H	X			
10.5	Release Note	LEAQ012		YES	H	H	H				X	
10.6	Review data book				R		H	R				

APPENDIX C: NATIONAL FORUM QUESTIONNAIRES

Public Perception Questionnaire 2019

National Forum – Darvill Direct Potable Reuse Learning Hub (WRC Project K5/2807)

Date: 26 November 2019

Location: Darvill Water Recovery Plant, Visitor Centre

Darvill Wastewater Works, New England Road, Pietermaritzburg

uMngeni-uThukela Water, together with the Water Research Commission, have developed a project to test reuse technologies and establish a national learning hub that will allow visitors to interact with the technologies through tours and demonstrations. This hub will help to establish public support for technologies, monitoring and the operational effectiveness of reclamation technology.

Please complete the following questionnaire relating to public perceptions of reclaimed water in South Africa. Be as objective and honest as possible. The questionnaire will take about 10 min to complete.

Answer the following questions or circle the most appropriate response and please specify when selecting 'Other'.

QUESTIONS:

1. What is your definition of reclaimed water?
   -
   ____
   ____

2. What in your opinion is the best application for reclaimed water?
   a) Agriculture b) Industrial c) Irrigation d) Drinking water e) Other (please specify)
   ____
   ____

3. What is your main concern when considering reclaimed water?

a) Public health b) Treatment costs c) Public acceptance d) Plant operational skills e) Other
____

4. What type of source water should be reclaimed in the event of a drought?
   a) Wastewater b) Greywater c) Rainwater d) Other (please specify)
   ______________________-
   ____
   ____

5. What specific area of research on reclaimed water would you like the project team to prioritise over the next 3-5 years?
   a) Emerging contaminants b) Operating and maintenance resiliency c) Control and monitoring
   d) Public perceptions e) Other (please specify)
   ______________________-
   ____

____

6. Which initiative would you classify as most critical towards gaining public support for use of reclaimed water?
   a) Environmental awareness b) Stakeholder education - National Forum c) Develop public perception strategies d) Further research e) Other (please specify)

   ____

   ____

7. What should be the frequency of stakeholder events such as this National Forum?
   a) 3 monthly b) 4 monthly c) 6 monthly d) Yearly e) Other ____________________

8. What do you think should be included at future National Forums?

   ____

   ____

   ____

9. General Comments?

Public Perception Questionnaire 2020

National Forum – Darvill Direct Potable Reuse Learning Hub (WRC Project K5/2807)

Online Questionnaire

Background Information:

1. What is your age? ____________
2. Gender ____________
3. Education ____________

Questions:

1. What type of source water should be reclaimed in the event of a drought and water shortage?

Wastewater Rainwater All

2. What is your view on the idea of using reclaimed water (treated wastewater without an environmental buffer) in different sectors?

Strongly agree Agree Acceptable Disagree Strongly disagree

3. What is your main concern regarding reuse of reclaimed water?

Public health Plant operation and quality control Public acceptance Treatment cost

4. What in your opinion is the best application for reclaimed water? Please rank the following in order of preference:

Agriculture Industrial Drinking Water No-non potable household use

5. Do you trust local Water Management, Supply and Monitoring bodies (e.g. Municipalities and service providers) to be responsible for the treatment and reuse of the wastewater?

Yes No Not sure

6. What is a Critical initiative to gain public support for reuse?

Develop public perception Stakeholder education Further Research Environmental Awareness Other

7. In South African context, which media you do you think will be an effective media to distribute information pertaining to water reuse?

TV Radio Social Media

8. In your opinion what should be the main research area on reclaimed water? Please rank in order of preference.

Public perceptions Emerging contaminant Resilience of OM, control and monitoring

9. Please put your general comments and suggestions regarding this forum below.

___

___

___