WASTEWATER RECLAMATION FOR POTABLE REUSE

VOLUME 2: INTEGRATION OF MBR TECHNOLOGY WITH ADVANCED TREATMENT PROCESSES

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

Background and Motivation

There are a range of technologies and combinations of treatment technologies that can be used to reclaim water from domestic wastewater effluent. The choice of treatment train that will meet quality, cost and operational requirements is thus a difficult one. The intention of this research project is to test a range of treatment technologies in different combinations and to establish a preferred reclamation treatment process train for water reclamation. The product water quality derived from the reclamation process should meet both South African and international drinking water standards. Water reclamation is being considered as an option to meet growing water supply demands. Although indirect potable reuse (IPR) projects are widespread, direct potable reuse (DPR) is still only practiced in two places in Southern Africa. It is envisaged that the results from this study will provide evidence and affirmation that the highest quality drinking water can be produced regardless of the quality of the source water.

Objective

The objective of this research project was to consistently produce acceptable potable drinking water through wastewater reclamation. The project is divided into two phases as follows:

- **Phase 1**: Bench-scale evaluation of advanced water treatment technologies for the production of potable water using membrane bioreactor technology as pre-treatment and in combination with the following technologies: ozone (O_3), granular activated carbon (GAC), nanofiltration (NF) / reverse osmosis (RO), and advanced oxidation (hydrogen peroxide & ultra-violet (UV) radiation).
- **Phase 2**: Recommend a wastewater reclamation treatment train for the design of a full scale reclamation plant and provide a capital and operating cost estimate.

Methodology

In previous work, (Volume 1: Evaluation of membrane bioreactor technology for pre-treatment), an assessment of MBR technologies as a pre-treatment step in wastewater reclamation was conducted. The Toray MBR demonstration plant proved to be the most reliable and easy to operate of the pilot plants evaluated and was therefore selected to be used for pre-treatment for all the water reclamation plant pilot trials carried out in this project. Bench-scale advanced water treatment unit processes were set up adjacent to the MBR pilot plant facility, and permeate from the facility was used to supply these unit processes with a constant feed. Various combinations of advanced water treatment technologies were trialled in continuous and batch tests, namely:

- Process A: MBR-RO-UV
- Process B: MBR-O3/GAC-NF-UV
- Process C: MBR-NF-O3/GAC-UV
- Process D: MBR-NF-UV
- Process E: MBR-O3/GAC-UF-UV

Routine water quality samples were taken on a daily basis, from the feed, from the final product water and from individual unit processes, and analysed. The various treatment trains were spiked with a number of micro-organics to determine the percentage removal of these potentially harmful endocrine disrupting compounds. Water quality samples taken were sent to the University of the Western Cape for analysis using the Enzyme Linked Immunosorbent Assay (ELISA) technique.

Summary of Results

The primary objective of this study was to determine the efficacy of various treatment trains and individual unit processes in meeting set water quality objectives, including the removal of CECs (endocrine disruptors, pharmaceuticals, and personal care products), for the production of potable water. Most of the treatment trains performed equally well in terms of the final potable water quality produced. Although there were minor differences in product water quality between the processes, most were compliant with the SANS 241 (2011) drinking water standard. The experimental results suggest that streamlined process trains such as MBR-RO-UV (replicating the Singapore process) or MBR-NF-UV are equally effective as treatment trains with additional processes such as ozonation and GAC (MBR-O3/GAC-NF-UV). Process A: MBR-RO-UV, the membrane-based process, would require less capital investment than process B: MBR-O_3/GAC-NF-UV, the ozone/GAC-based treatment process, based on the cost estimate. The difference in capital cost is, however, marginal at this level of accuracy. The operating cost for process A is also marginally lower.

The disadvantage of the membrane-based (NF/RO) process trains is the additional cost of brine disposal. In coastal environments disposing of the brine to sea is most likely to be a feasible and cost effective option as the concentrate has a far lower TDS concentration (3,700 mg/l) than the sea (35,000 mg/l). MBR-RO-UV and MBR-NF-UV are thus recommended reclamation processes for coastal environments. Membrane-based process trains (NF/RO) are not feasible inland because of the cost of treating and disposing of the brine. O_3/GAC-based treatment trains are therefore recommended for inland reclamation schemes. The NF membrane used in processes B & C will have to be replaced by a UF membrane to avoid the brine disposal problem. As the MBR-O_3/GAC-UF-UV (process E) was not part of the original scope of work, only limited results have been obtained for this train. The process is, however, very similar to the Goreangab Water Reclamation Plant and therefore, this train has potential and should be investigated further. The Goreangab Water Reclamation Plant does not have an advanced oxidation process (UV/H_2O_2), so the proposed process E treatment train has an additional barrier. The replacement of the RO and NF membrane with a UF membrane will reduce the cost significantly. Although UF does not remove micro-organic substances there are three barriers, namely ozonation, GAC and advanced oxidation processes (AOP) that provide this protection.

It is thus proposed that further trials be conducted to test the performance of this proposed treatment train. If reclamation is to be considered an alternative treatment train such as MBR-O_3/GAC-UF-UV will have to be considered.

Conclusions and Recommendations

All the process trains proposed and tested recorded zero values for *E.coli* and coliphages in the final product water, throughout the trials. The level of trace organics was also consistently reduced by greater than 96% for the range of contaminants tested. Although the multiple-barrier approach is universally supported, the more streamlined MBR-RO-AOP (UV/H_2O_2) process was demonstrated to be highly effective at achieving the goal of delivering safe drinking water consistently, throughout the course of this research. Membrane-based treatments coupled with advanced oxidation offer numerous advantages over more conventional multiple-barrier reclamation schemes.

Wastewater influent is often of variable quality and membrane-based process trains are reliable in delivering high quality water, enhanced process stability and ease of continuous quality monitoring. Membrane-based schemes also offer flexibility in relation to changing water quality demands, which can be dealt with by future technological upgrades. Supporting the MBR-RO-AOP process with other associated best practices is fundamental to creating a successful reclamation scheme. Managing the quality of the raw water influent, continuous monitoring and engineered buffering are but a few of the additional measures that can be implemented. The MBR-RO-AOP (UV/H_2O_2) process train is recommended for reclamation schemes where brine disposal can be managed cost effectively. The alternative process, MBR-O_3/GAC-UF-UV, is recommended for scenarios such as inland wastewater works, where brine treatment and disposal is not an option, or not economically feasible.

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ACRONYMS, ABBREVIATIONS AND SYMBOLS

AOC	Assimilable Organic Carbon
AOP	Advanced Oxidation Process
ASP	Activated Sludge Process
ASTs	Activated Sludge Tanks
BAC	Biological Activated Carbon
BOD	Biochemical Oxygen Demand
CAS	Conventional Activated Sludge
CEC	Contaminants of Emerging Concern
CFC	Coagulation/Flocculation/Clarification
CFU	Colony Forming Unit
CIP	Cleaning in Place
COD	Chemical Oxygen Demand
DAF	Dissolved Air Flotation
DBP	Disinfection By-products
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DPR	Direct Potable Reuse
EBCT	Empty Bed Contact Time
EDC	Endocrine Disrupting Compound
ELISA	Enzyme Linked Immunosorbent Assay
F:M Ratio	Food to Mass Ratio
FS	Flat Sheet
GAC	Granular Activated Carbon
H_2O_2	Hydrogen Peroxide
HDPE	High Density Polyethylene
HF	Hollow Fibre
HRT	Hydraulic Retention Time
IPR	Indirect Potable Reuse
LC-OCD	Liquid Chromatography–Organic Carbon Detection
LMH	Litres per square metre per hour
LRV	Log Removal Value
MBR	Membrane Bioreactor
MF	Microfiltration
MLSS	Mixed Liquor Suspended Solids
MWCO	Molecular Weight Cut-off
NDMA	Nitrosodimethylamine
NF	Nanofiltration

NGWRP	New Goreangab Water Reclamation Plant
NH_3	Ammonia
NH_4-N	Ammonium-N
NO_3	Nitrate
NOM	Natural Organic Matter
NTU	Nephelometric Turbidity Units
O&M	Operation and Maintenance
O_3	Ozone
OCWD	Orange County Water District
PFU	Plaque Forming Unit
PLC	Programmable Logic Control
PPCPs	Pharmaceuticals and Personal Care Products
PVDF	Polyvinylidene Fluoride
RAS	Return Activated Sludge
RO	Reverse Osmosis
SAD_m	Specific aeration demand based on membrane area
SAD_p	Specific aeration demand based on permeate volume
SCADA	Supervisory Control and Data Acquisition
SDI	Silt Density Index
SRP	Soluble Reactive Phosphorous
SRT	Solids Retention Time
TDS	Total Dissolved Solids
THMs	Trihalomethanes
TKN	Total Kjeldahl Nitrogen
TMP	Trans Membrane Pressure
TOC	Total Organic Carbon
TP	Total Phosphorous
TSS	Total Suspended Solids
UF	Ultrafiltration
USEPA	United States Environmental Protection Agency
UV	Ultra Violet
UWC	University of the Western Cape
WHO	World Health Organisation
WRC	Water Research Commission
WWW	Wastewater Works

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

Direct potable reuse (DPR) normally requires a higher level of treatment than traditional surface or groundwater sources because of the nature of the source water. By its very nature, wastewater, e.g. domestic sewage, contains contaminants that occur at far higher concentrations than one would expect to find in traditional water sources. Groundwater, for example, can be of such a good quality that it can be consumed without treatment, as is the case in many places in the world. The diversity of contaminants in wastewater is of concern to water service providers and public health authorities. A wide variety of potentially harmful pollutants may be present in wastewater influent streams. More recently, awareness of the risks associated with the drinking of wastewater has been magnified by ever increasing evidence of the presence of potentially harmful organic contaminants. Public safety is of paramount importance in the design of drinking water systems for the treatment of wastewater. To this end, advanced water treatment systems have been developed to deal with the removal of harmful substances and ensure safe drinking water. The literature review in this section focuses on some of the contaminants that must be removed when planning a DPR system and also on the type of treatment technologies that can be effective in achieving the objective of safe potable drinking water.

It is, however, important to consider that all water discharged to surface and groundwater, from point and non-point sources, is basically a form of Indirect Potable Reuse (IPR). In recent surveys of surface and groundwater quality by the US Geological Survey (Barnes et al., 2008), it was concluded that essentially all surface and groundwater is contaminated with chemicals commonly associated with wastewater, such as pharmaceuticals. In the future, it is anticipated that surface and groundwater discharges will need to comply with much more stringent discharge requirements, to protect the environment. The level of treatment needed to protect environmental species and ecosystems may, in some cases, be higher than that needed for DPR. Thus, the implementation of DPR may make more sense environmentally than the discharge of purified water to the aquatic environment (Leverenz et al., 2011).

1.2 AIMS

The main aim of this research project is to consistently produce acceptable, potable drinking water through wastewater reclamation. The project is divided into two phases as follows:

- **Phase 1**: Bench-scale evaluation of advanced water treatment technologies for the production of potable water using membrane bioreactor technology (as pre-treatment) and in combination with the following technologies: ozone (O_3), granular activated carbon (GAC), nanofiltration (NF)/reverse osmosis (RO) and advanced oxidation processes (AOP): hydrogen and ultra-violet (UV) radiation.
- **Phase 2**: Recommend a wastewater reclamation treatment train for the design of a full scale water reclamation plant, and provide a capital and operating cost estimate.

1.3 APPROACH

Combinations of the above treatment technologies were tested in various treatment trains to ascertain if they could consistently produce potable water and to determine if there was any difference in the quality of water produced. A brief summary of the work undertaken in this project is as follows:

1. **Proof of MBR concept**

Results from the evaluation of membrane bioreactor technology for pre-treatment are detailed in Volume 1 (**Report No. 1894/1/14**). Three MBR pilot plants, from different manufacturers, were rented and set up onsite at the Darvill WWW The performance of the Toray and Norit MBR systems was evaluated. The permeate water quality produced by the pilot plant MBRs was of a high quality and met the target water quality objectives, with a few exceptions; for example the target level of removing nitrate to below 6 mg/l could not always be achieved. There were a number of reasons for this but over aeration of the anoxic zone was considered to be a major contributor to poor denitrification. The treatment shortcomings of the MBR pilot plants were not considered critical in terms of the desired effluent water quality. Those constituents such as chemical oxygen demand (COD), total organic carbon (TOC) and turbidity that could potentially impact on membrane fouling were removed to a sufficient extent. The MBR process shortcomings were also considered to be related to scale and would be overcome on full scale plants. The performance of a range of MBRs, by different manufacturers, used on pilot plants and full scale plants around the world confirmed the quality of MBR permeates. The researchers were thus satisfied that the MBR permeate being produced from the pilot MBR plants at Darvill would be suitable for the next phase of the study (reported in the present report). In phase 2 laboratory scale pilot trials, MBR technology was used in combination with the following advanced treatment technologies:

- Ozonation
- Granular activated carbon
- Nanofiltration
- Reverse osmosis
- Advanced oxidation processes.

2. **Laboratory scale trials of ozone/granular activated carbon (O_3/GAC) and membranes as a batch process: June 2011 through to June 2012 (High performance NF and RO membranes selected for continuous trials); (current report);**

3. **Continuous flow spiral wound membrane (NF and RO) trials June 2012 through to September 2012; (including studies of endocrine disrupting compounds (EDCs)); (current report);**

4. **Alternative treatment train (MBR-NF-O_3/GAC-UV) trials: October 2012 through to March 2013; (current report).**

CHAPTER 2: LITERATURE REVIEW

2.1 CONTAMINANTS OF EMERGING CONCERN

Contaminants of Emerging Concern (CECs) are a broad classification for pharmaceuticals and EDCs, which are subclasses of organic contaminants that have been detected in wastewater and surface waters throughout the world (Benotti et al., 2009, Snyder & Benotti, 2010, Kumar & Xagoraraki, 2010). Their occurrence is most often a result of municipal wastewater discharge, as these compounds are not completely removed during treatment. Other sources of CECs in water include runoff from agricultural fields and feedlots, landfill leachates, and urban runoff. Water authorities, scientists, public health organisations and civil society are concerned about what level of risk may be associated with the presence of CECs in drinking water, as many drinking water treatment plants use source water impacted by wastewater (US Bureau of Reclamation, 2009). In fact CECs can occur in finished drinking water in greater numbers (categories) than in the surface water sources (Kumar & Xagoraraki, 2010). While some researchers have postulated that the long-term risk to humans from any single pharmaceutical at sub-µg/l levels is negligible, it is not clear what toxicological implications chronic exposure to suites of trace contaminants may pose (Snyder et al., 2003*)*.

The ability of a particular treatment process to remove organic contaminants depends mostly on the structure and concentration of the contaminant. Chemical oxidation (during drinking water applications), biological removal/transformation (during wastewater applications), or NF/RO are the water treatment technologies most responsible for CEC removal; the operational parameters of the process (e.g. oxidant dose and contact time) will determine the degree of attenuation of a particular contaminant (Snyder and Benotti, 2010). Table 2.1 shows the relative performance of water and wastewater treatment technologies in removing various categories of CECs. Reverse osmosis (RO) membranes, for example, can remove more than 95% of most organics compounds. Nitrosodimethylamine (NDMA), with a molecular weight of 74, is among the organic chemicals with a low level of removal (25-50%) by RO. The technologies listed in Table 2.1 are sometimes known as tertiary treatment or advanced water treatment technologies, which sets them apart from conventional treatment technologies such as coagulation/flocculation, sedimentation, sand filtration, activated sludge and clarification. These advanced technologies are becoming more widely used, as more sophisticated treatment options are required to deal with a degradation in source water quality. The performance of these advanced water treatment technologies is especially relevant because of their ability to remove CECs, as is illustrated by the high percentage removal rates recorded in Table 2.1.

Table 2.1: Indicative Removal of Organic Chemicals

Treatment	Percentage Removal										
		Pharmaceuticals				Hormones					
	B(a)p	Antibiotics[a]	DZP	CBZ	DCF	IBP	PCT	Steroid	Anabolic[c]	Fragrance	DBPs NDMA
Secondary Activated Sludge	nd	10-50	nd	-	10-50	>90	nd	>90	nd	50-90	-
Microfiltration	nd	<20	<20	<20	<20	<20	<20	<20	nd	<20	
UF/PAC	nd	>90	>90	>90	>90	>90	nd	>90	nd	>90	>90
Nanofiltration	>80	50-80	50-80	50-80	50-80	50-80	50-80	50-80	50-80	50-80	
Reverse Osmosis	>80	>95	>95	>95	>95	>95	>95	>95	>95	>95	20-50
GAC		>90	>90	>90	>90	>90		>90		>90	>90
Ozonation	>80	>95	50-80	50-80	>95	50-80	>95	>95	>80	50-90	50-90
Advanced Oxidation		50-80	50-80	>80	>80	>80	>80	>80	>80	50-80	>90
High-level UV		20-80	<20	20-50	>80	20-50	>80	>80	20-50	nd	>90
Chlorination	>80	>80	20-50	<20	>80	<20	>80	>80	<20	20-80	

DZP-Diazepam, CBZ-Carbamezepine, DCF-Diclofenac, IBP-Ibuprofen, DBP-Disinfection By-products, NDMA-Nitrosodimethylamin

2.2 ADVANCED WATER TREATMENT TECHNOLOGIES

Improvements in water treatment technologies and analytical capabilities have made it possible to validate the concept that water can be purified using several alternative process flow schemes. The basic system used to purify wastewater consists of several processes collectively referred to as advanced treatment. The current advanced treatment scheme has evolved over time, and now commonly includes microfiltration (MF), reverse osmosis and advanced oxidation (Leverenz et al., 2011). The advanced wastewater treatment processes pertinent to this study are discussed in the sections that follow. A brief description of each technology is given, with some references to the recorded performance of these technologies in experimental, pilot or full scale situations. Special reference is given to the performance of these technologies in removing CECs, such as EDCs and pharmaceutical and personal care products (PPCPs). It should be noted that CECs are often referred to as trace organics or micro-organics in the literature. The terms are thus used interchangeably in this report.

2.2.1 Membrane Bioreactors

Membrane bioreactors make use of a polymeric membrane to achieve the solids – liquid separation at the end of the activated sludge process. The pores in the MBR are of such a size that they exclude all solids, allowing only the passage of dissolved substances. As a result, bacteria, and protozoa such as *Giardia lamblia* and *Cryptosporidium parvum* are excluded. The two protozoa are of particular significance as they cause severe diarrhea which can result in death immuno-compromised persons. The ability of MBRs to remove hardly biodegradable trace organics such as steroids, pharmaceuticals or personal care products has been investigated by many groups, and compared with the performance of conventional activated sludge plants *(*Lesjean et al., 2004). This was motivated by the expectation that the complete retention of microorganisms by the membrane would facilitate the enrichment of specialists which would be able to feed on hardly biodegradable compounds present at concentration ranges of ng/l up to µg/l.

The nominal molecular weight cut-off (NMWCO) of ultrafiltration membranes has no influence on the elimination of these substances with the possible exception of very tight membranes, e.g. MWCO < 100 kDa When MF and UF membranes with various pore sizes were compared in anaerobic digester broth filtration, there was no noticeable difference in permeate quality (Imasaka et al., 1989). A potential reason could be the shift of NMWCO of the membranes due to the gel layer that forms during the operation. Due to the physical properties of these substances it is expected that adsorption onto bio-solids and organics of activated sludge may occur *(*Clara et al., 2005). For instance, MBR systems combined with post-treatment steps like NF and activated carbon adsorption were shown to be more effective for removal of nonylphenol and bisphenol-A (also EDCs) than RO alone (Wintgens et al., 2008). However, recent investigations (Clara et al., 2005) showed that, for a given sludge age, the MBR processes perform similarly to conventional activated sludge (CAS) systems.

2.2.2 Ozonation

Ozone is a strong oxidant and disinfectant that decays within minutes after addition to water. Ozonation is commonly used to achieve:

- Primary degradation – a structural change in the parent molecule
- Acceptable degradation (defusing) – a structural change in the parent compound to reduce toxicity
- Ultimate degradation (mineralization) – conversion of organic carbon to inorganic carbon or CO_2.

Aqueous ozone may react with various species in two manners: direct reaction by molecular ozone and indirect reaction through radical species formed when ozone decomposes in water (Mandel, 2007). This radical has a greater oxidizing capability than other, more conventional oxidants such as oxygen (atomic and molecular) and chlorine. In most cases complete oxidation of the organic compound is not necessary – partial oxidation of the molecule is sufficient to achieve subsequent biological treatment or to reduce the toxicity. Ozone reacts with natural organics to increase their biodegradability, measured as assimilable organic carbon (AOC). Ozone is effective at:

- inactivating pathogenic microorganisms such as giardia lamblia and viruses,
- inactivating cryptosporidium parvum *(*at high doses and with long contact times), and
- destroying several taste and odour causing compounds in water.

During ozonation tests by Snyder et al., most of the target compounds investigated showed over 80% removal at typical ozone dosages (2.7 mg/l) and were removed within five minutes of contact time. Lower ozone dosages (1.3 mg/l) were not nearly as effective (Snyder et al., 2003). As expected, electron-donating groups enhance the reactivity of aromatic compounds toward ozone, while electron-withdrawing groups inhibit the reactivity. As a result, all target compounds with phenolic structures, such as acetaminophen and several hormones were removed to below analytical detection limits. Androstenedione, progesterone and testosterone were stabilize less efficiently than any of the estrogen compounds due to ketone functional groups on these hormones, which decreases the reactivity of ozone with the adjacent carbons. Similar results were obtained during bench-scale drinking water treatment process experiments (Westerhoff et al., 2005).

Three drinking water supplies were spiked with 10 to 250 ng/l of 60 different EDC/PPCPs. Ozone oxidized steroids containing phenolic moieties (estradiol, ethynylestradiol, or estrone) more efficiently than steroids without aromatic or phenolic moieties (androstenedione, progesterone, and testosterone). EDC/PPCPs were separated into three general groups based on their reactivity with oxidants:

1) Compounds easily oxidized (> 80% reacted) by chlorine are always oxidezed at least as efficiently by ozone;

2) Compounds poorly oxidized (< 20% reacted) by chlorine or ozone; 6 of the 60 compounds (TCEP, BHC, chordane, dieldrin, heptachlor epoxide, musk ketone) were in this group;

3) Compounds reacting preferentially (higher removals) with ozone rather than chlorine; 24 of the 60 tested (e.g., DEET, ibuprofen, gemfibrozil) were in this group.

Other compounds (atrazine, Iopromide, meprobamate, TCEP), had low removals by all processes considered.

2.2.3 Granular Activated Carbon

GAC has an extremely high specific surface area and has an affinity for organic molecules. GAC is used to absorb the organic molecules dissolved in water. When molecules are absorbed onto the activated carbon surface they undergo migration throughout the pores of the carbon. Those contaminants with low aqueous solubility, and a size conducive to fitting within the pore structure, are most readily adsorbed. In the presence of oxygen, a biological mass develops on the carbon which biodegrades the absorbed organics. The biodegradation of the absorbed molecules results in the biological regeneration of the activated sludge, thus increasing its net absorption capacity. The porous structure of the activated carbon makes it an ideal host for a biomass.

The effectiveness of GAC in adsorbing a particular chemical can generally be predicted based on how hydrophilic (water loving) or hydrophobic (water repelling) a chemical is. GAC is effective for the removal of a diverse range of hydrophobic organic compounds, as well as some relatively hydrophilic inorganic compounds such as nitrogen, sulphides and heavy metals. More hydrophilic compounds, such as carboxylic acids and alcohols, are relatively poorly removed by GAC (Metcalf and Eddy, 2004). GAC can be highly effective for the removal of a wide range of pharmaceuticals, hormones and pesticides (Table 2.1), but does not greatly reduce concentrations of salts and nutrients. GAC is a US Environmental Protection Agency best available technique (BAT) for the following contaminants:

- Disinfection by-products (DBPs)
- Mercury and cadmium
- Natural organic matter (NOM)
- Synthetic organic chemicals (specifically; benzo(a)pyrene, di(2-ethylhexyl)adipate, di(2-ethylhexyl)phthalate, hexachlorobenzene, dioxin)
- Radionuclides.

Biological growth within the GAC results in what is known as biologically activated carbon (BAC). BAC can be beneficial by removing AOC and other biodegradable compounds. If it is intended to have BAC, the GAC filters are typically preceded by ozonation that breaks down the organic carbon into a more assimilable form. This process can enhance the overall contaminant removal of the GAC process. The addition of ozone not only increases the biodegradability of the dissolved organics, but also introduces large amounts of oxygen into the water, thus creating an excellent environment for biological growth on the filter media (Techneau, 2006). A study in Australia (Reungoat et al., 2012) investigated the fate of CECs in three full scale reclamation plants where ozonation followed by BAC filtration was used to treat wastewater treatment plant effluents. Limited dissolved organic carbon (DOC) removal (<10%) was observed in the ozonation stages, showing that oxidation leads to the formation of transformation products rather than mineralization. The degree that the quantified CECs were removed was highly dependent on the compounds’ structures and the specific ozone dose.

The subsequent BAC filtration removed between 20% and 50% of the DOC. Overall, the combination of ozonation and BAC filtration can achieve removal of 50% for DOC and more than 90% for a wide range of CECs. This is corroborated by work done by Snyder et al. (2007), in bench-scale experiments of the adsorption of 29 CECs, which demonstrated that GAC was capable of providing greater than 90% removal of nearly all compounds. Increasing the ozone dose and filtration empty bed contact time (EBCT) generally has a positive influence on the removal of DOC and CECs, but there is no direct linear relationship. Therefore, increasing the ozone dose and EBCT further will not necessarily lead to substantive gains in water quality.

2.2.4 Nanofiltration and Reverse Osmosis

NF membranes have nominal pore sizes in the range 0.001–0.01 microns. The fundamental basis for removal of chemicals is size exclusion, although electrostatic repulsion and hydrophobic adsorption can also contribute to removal (Ozaki, 2002). Molecular weight cut-offs are of the order of 600 atomic mass units. NF can provide greater than 6-log reductions of bacterial, viral and protozoan pathogens. However, as with all membrane filtration, there are limitations on the log reductions that can be demonstrated by operational procedures. As shown in Table 2.1, NF membranes can remove 50–80% of organic compounds. At present, it is clear that small neutral organic compounds are not rejected by NF membranes as efficiently as dissociated salts or charge-bearing organic molecules (Ben-David et al., 2010).

RO membranes remove dissolved organic compounds in a process driven by a pressure gradient that forces molecules across semipermeable membranes. The fundamental basis of removal is size exclusion, particularly for molecules such as surfactants, hormones and most pharmaceuticals with molecular weights greater than 100–200 atomic mass units. Electrostatic repulsion, hydrophobic adsorption and chemical shape also contribute to removal, particularly for low molecular weight compounds. As shown in Table 2.1, RO membranes can remove more than 95% of most organics compounds. Nitrosodimethylamine (NDMA), with a molecular weight of 74, is among the organic chemicals with a low level of removal (25–50%). RO can provide greater than 6-log reductions of bacterial, viral and protozoan pathogens. Typically, the operation of RO membranes is monitored using electrical conductivity or total carbon concentrations.

Kimura et al. (2003) found negatively charged compounds to be significantly rejected by NF/RO membranes due to electrostatic repulsion between the compounds and membranes. The high rejection (> 90%) associated with negative charge was observed even when compounds with small molecular weights and rather loose membranes were examined. Snyder et al. (2007) investigated the removal of 36 EDCs and PPCPs during drinking and wastewater treatment processes at pilot and full scale and found that RO and NF membranes were capable of rejecting most of the compounds studied to below detection levels (< 25 ng/l). Wintgens et al. (2008) reported on the performance of NF and RO membranes in removing organic contaminants included estrone, ethinylestradiol, estradiol and sulphamethoxazole. Selected results that allow comparison with this study are listed in Table 2.2.

Table 2.2: Performance of NF and RO Membranes

Compounds	Substance Type	Membrane Type	Retention (%)
Estrone	EDC	NF/RO	13 - >80
Estrone	EDC	NF	80 - >95
Estrone	EDC	NF	65 – 83
Estrone	EDC	NF	40 - >99
Estradiol	EDC	NF	20 - >80
Estradiol	EDC	NF	49 - >99
Estradiol	EDC	RO	29 – 83
Ethinylestradiol	EDC	NF	41 - >99
Sulphamethoxazole	Pharmaceutical	RO	70 – 82

Among the emerging technologies for indirect potable use, nanofiltration should be highlighted as a treatment technology which can remove a wide range of microbiological as well as chemical contaminants (Schafer et al., 2005). NF can be considered as an alternative to RO technology where a lower degree of desalination is required. With a molecular weight cut-off above 200 g/mol it is a promising treatment option for a variety of emerging trace contaminants. NF has been investigated in a number of purification applications.

2.2.5 Advanced Oxidation Processes

Advanced oxidation refers to the use of high level oxidative processes to degrade organic constituents of wastewater that are biologically persistent and poorly retained by membranes or activated carbon. Typically, advanced oxidation incorporates combinations of high doses of UV light or ozone with hydrogen peroxide to produce highly reactive hydroxyl radicals. Each of these processes independently degrades organic compounds, but the formation of hydroxyl radicals greatly improves degradation. The effectiveness of advanced oxidation depends on the contact time and concentration of scavengers in the water (i.e. non-target oxidizable species). Dissolved organic carbon and carbonate or bicarbonate are generally the most important scavengers in drinking water. Pre-treatment processes such as GAC or RO significantly increase oxidation efficiency. Advanced oxidation has been shown to be highly effective in degrading organic chemicals, such as NDMA, that pass through RO membranes. For reclaimed water systems, the recommended design UV doses are 100 mJ/cm^2 for granular media filtration effluent, 80 mJ/cm^2 for membrane filtration effluent, and 50 mJ/cm^2 for RO effluent. The different dose requirements reflect the different virus density concentration expected within each type of process effluent. The dosages selected are intended to provide 4 logs of poliovirus inactivation with a factor of safety of about 2. In addition to differing dose recommendations as a function of effluent quality, there are differing design transmittance recommendations. For GM, MF and RO effluents, the design transmittances are 55, 65, and 90 per cent, respectively.

A UV dosage of 60 mJ/cm^2 and 250 mJ/cm^2 is applied at NEWater Singapore and Beaufort West reclamation plants respectively. The World Health Organisation (WHO) drinking water quality guidelines

(2008) specifies a requirement of 59 mJ/cm^2 for 99% inactivation of viruses, protozoa and bacteria. Snyder et al. (2003) showed that UV is not able to provide significant removal of most target analytes under a common disinfection dose of 40 mJ/cm^2. Higher removal efficiencies (85%) can be achieved with UV when it is coupled with hydrogen peroxide ($H_2O_{2)}$ as an advanced oxidation process (AOP). UV/H_2O_2 is extremely effective in the removal of steroid estrogens and their derivatives, achieving removal rates greater than 98%. It is equally effective in the removal of progesterone and testosterone, with removal rates of greater than 97% (US Bureau of Reclamation, 2009). The chemical structure of the target analyte controls whether it can be oxidized by UV light. The conjugated aromatic structure of diclofenac and triclosan causes these two compounds to exhibit relatively higher removal (50-65%). Phenolic compounds are amenable to oxidation treatment. Experiments were conducted in which the UV and H_2O_2 were adjusted in UV-AOP with the addition of H_2O_2. A constant UV dose of approximately 370 mJ/cm^2 was applied with H_2O_2 doses of 5.8 and 7.6 mg/l. Interestingly, the increase in H_2O_2 at a constant UV dose did not offer a large increase in contaminant removal. An increase in the UV dose to approximately 540 mJ/cm^2 with a hydrogen peroxide dose of 7.5 mg/l showed a modest increase in contaminant oxidation. The data in Table 2.3 demonstrate diminishing returns with large increases in UV and H_2O_2 doses, suggesting that lower doses may provide nearly equivalent contaminant reduction with less energy and peroxide cost (Snyder et al., 2003).

Table 2.3: Medium Pressure UV AOP Pilot Removal Percentages

UV Dose (mJ/cm^2)	216	366	379	537
Peroxide Dose (mg/l)	4.6	5.8	7.6	7.5
Percentage Removal (%)				
Androstenedione	81	83	89	96
Atrazine	61	61	67	80
Caffeine	66	68	76	89
Carbamazepine	16	49	67	>88
DEET	64	67	78	89
Diazepam	73	74	81	93
Dilantin	84	86	91	97
Erythromycin	0	35	19	64
Fluoxetine	92	93	96	>98
Gemfibrozil	76	78	85	95
Ibuprofen	73	74	83	94
Iopromide	76	80	79	91
Meprobamate	48	45	58	75
Pentoxifylline	68	68	78	90
Progesterone	84	86	91	98
Sulfamethoxazole	95	97	97	>99
TCEP	10	0	8	16
Testosterone	83	85	90	97
Trimethoprim	76	77	85	94

2.2.6 Chlorination

Work done by Renew and Ching-Hua (2004) suggests that chlorine may eliminate antibiotics more efficiently than UV treatment. These results are consistent with bench-scale experiments that illustrate high susceptibility of fluoroquinolones, sulphonamides and trimethoprim to reactions with chlorine and low susceptibility of fluoroquinolones and trimethoprim to photolysis at typical dosages of UV disinfection.

2.3 WATER RECLAMATION PROCESS CONFIGURATIONS: CASE STUDIES

There are a number of indirect and direct water reuse schemes in the world. The most famous direct reuse project is the Goreangab Water Reclamation Plant, in Windhoek, Namibia, which has been operational since 1968. Until recently, this scheme was the only direct reuse plant in the world, but it has now been joined by the Beaufort West Reclamation Plant in South Africa. Of the indirect reuse projects, the NEWater project in Singapore has received a lot of attention in recent times. The NEWater project releases reclaimed water into a reservoir, which is then abstracted and treated at a conventional water treatment plant. An equally successful indirect reuse scheme, which has been operating for a far longer period, is the Orange County Water District (OCWD) reclamation project in California, which uses reclaimed water to supplement existing supplies through artificial recharge of aquifers used for drinking water. Another indirect reuse project completed recently is the Western Corridor Recycling Project in Queensland, Australia. These projects provide a wealth of information regarding appropriate treatment technologies and the appropriate operational protocols required to ensure the supply of safe drinking water through reclamation. They are looked at in more detail in the following section as they provide a benchmark for this study and for the development of future reuse projects in general.

2.3.1 New Goreangab Water Reclamation Plant

The New Goreangab Water Reclamation Plant in Windhoek is the most famous wastewater reclamation plant in the world, as for decades Windhoek was the only city in the world directly reclaiming treated wastewater effluent for drinking water. The New Goreangab Water Reclamation Plant (NGWRP), as it is known today, after many upgrades, has the process train shown in Table 2.4 below.

Table 2.4: Process Configuration for New Goreangab Reclamation Plant

NGRP
Pre-ozonation and Dissolved Air Flotation
Rapid Sand Filtration and Ozonation
Biological Activated Carbon and Granular Activated Carbon
Ultrafiltration
Stabilization and Chlorine

The successful operation of the NGWRP lies in the application of the multiple-barrier principle. Three types of barriers can be distinguished: non-treatment, treatment and operational. It should be noted that barriers in this sense mostly cannot imply absolute dead-stop barriers. Non-treatment barriers, to name but a few, include:

- the diversion of industrial effluent to a different drainage area, and the policing of industrial discharges;
- rigorous continuous quality monitoring of the raw and treated water to allow for corrective action to protect the consumer;
- blending of reclaimed water with water from conventional sources, to limit reclaimed water to a maximum of 35% of the blended water.

Treatment barriers are always against specific contaminants and are regarded as either partial or complete. Different contaminants respond differently to different treatment methods. Operational barriers provide backup capacity to an existing process. The NGWRP process train provides for the following:

- Two complete barriers against turbidity (DAF/filtration and membrane filtration)
- Three complete barriers against microbiological contaminants (ozone, membrane filtration, chlorination)
- Four complete barriers against giardia (DAF/filtration, ozonation, membrane filtration, chlorination)
- Two complete barriers and two partial barriers against cryptosporidium (DAF/filtration and membrane filtration as complete barriers; ozonation and chlorination as partial barriers)
- Four partial barriers against organic contaminants (enhanced coagulation, ozonation, GAC adsorption, and some DOC rejection by membrane filtration).

The NGWRP water quality treatment objectives are provided in Annexure B-A for comparison purposes.

2.3.2 Orange County Water District

The Orange County Water District groundwater replenishment system in California is one of the largest water reclamation facilities in the world, with a current capacity of 114 Ml/day. The raw water source is secondary effluent from a wastewater works. Two treatment processes are in operation for use in achieving drinking water standards for the product water:

- Lime clarification, recarbonation, multimedia filtration, RO, and disinfection.
- MF, RO, disinfection.

The treated water is used for aquifer recharge to protect a groundwater resource from seawater intrusion. From the above it can be seen that the longer, conventional process involving clarification, recarbonation and filtration can be replaced by MF. MF followed by RO is all that is required to achieve a product water of drinking water standard. Operationally, run times for RO between membrane cleanings were approximately the same for the two pre-treatment systems. However, costs for microfiltration are about 45% lower than for lime clarification, recarbonation, and filtration, at 0.22 and 0.42 US$/m^3 respectively (Lazarova et al., 2003). The higher capital costs of MF elements are more than offset by the lower operation and maintenance costs of this advanced technology. Another important advantage of MF is the consistent filtrate quality despite wide variations in feedstream wastewater composition: generally around 0.05 NTU, with a maximum of about 0.1 when high influent turbidity was observed over periods of several months. The conductivity and silt density index (SDI) is consistently lower for MF pre-treatment effluent compared to conventional lime pre-treatment. In addition, operator input is minimal, making remote, unattended operation possible (Lazarova et al., 1998). The product water quality is presented in Table 2.5 below. It is noteworthy that the trace organic compounds that are detected in the final product water are, primarily, disinfection by-products, such as chloroform and bromoform. The organics detected are, however, considerably below maximum allowable contaminant levels.

Table 2.5: Monthly Average Water Quality Data of OWCD Product Water

Parameter	Units	Measured
Turbidity	NTU	0.07-0.49
pH	pH units	7.7-8.2
TOC	mg/l	0.3-1.1
TSS	mg/l	ND-0.1
TDS	mg/l	28-236

2.3.3 Singapore NEWater Project

A dual UF or MF–RO membrane process plus UV radiation has been successfully applied to produce high grade water from secondary treated effluent in Singapore, since May 2000. Prior to implementation of the project, a comprehensive study to evaluate the feasibility of using dual-membrane technology to reliably produce reclaimed water from municipal effluent was conducted. The study was conducted at a purpose built 10 Ml/day demonstration facility at the Bedok Water Reclamation Plant. Source water to the plant is clarified secondary effluent from an activated sludge treatment process that typically contains: 10 mg/l biochemical oxygen demand (BOD), 6.4 mg/l ammonia, 15 mg/l total suspended solids (TSS) and 12 mg/l total organic carbon (TOC) (Qin et al., 2009). The NEWater demonstration plant water quality results are provided in annexure B-A. Table 2.6 below provides a comparison of design and actual operating parameters.

Table 2.6: Design & Actual Operating Parameters. Singapore NEWater Project. (Aug 2000)

Parameter	Specified Design	Actual
TOC Removal (%)	>97	>99
Ammonia Removal (%)	>90	96
TDS Removal (%)	>97	96
MF Filtrate Turbidity (NTU)	<0.1	<0.1

2.3.4 Western Corridor Recycling Water Project

The Western Corridor Recycling Water Project in Queensland, Australia, is reported to be the largest recycled water scheme in the southern hemisphere. It aims to reduce demand on the region's fresh water supply while securing water supplies for industrial use and reducing the environmental impact on water resources. The Bundamba Advanced Water Treatment Plant uses state-of-the-art technologies to improve the quality of secondary-treated sewage water, for reuse as potable water and industrial cooling water. It includes: flow equalization, pre-treatment (coagulation and clarification for phosphate and turbidity removal), microfiltration, reverse osmosis, advanced oxidation (hydrogen peroxide and UV dosing) and final stabilization of the water. Testing was undertaken for 400 pharmaceuticals, herbicides, pesticides and other inorganic and organic compounds. Ninety-five per cent of these compounds were detected in the treated wastewater prior to treatment at the advanced water treatment plant. The majority of these chemical compounds were not detected in the purified recycled water.

Table 2.7 contains a list of chemical compounds that were detected in the purified recycled water. The levels of these detected chemicals are within the limits of the Public Health Regulation (2005), and pose no acute or long-term risk to public health. No hormones and no pathogenic microorganisms were detected in the purified recycled water. Some of the salient final water quality results are at their median values: 140 mg/l TDS, turbidity 0.4 NTU, zero colony forming units (CFU)/100ml of *E.coli* and zero plaque forming units (PFU)/100ml of coliphages. Australian studies have shown that the wastewater treatment processes used in South East Queensland remove 95-99% of endocrine disrupting compounds (EDCs). The advanced water treatment processes are highly effective at removing the EDCs that remain.

Table 2.7: Compounds in Purified Recycled Water; Western Corridor Recycling Water Project.

Inorganic Chemicals	aluminium, boron, cadmium copper	fluoride, iron, manganese sulphate
Disinfection By-products	bromate, bromodichloromethane chloroform	dibromochloromethane, dichloroacetic acid, NDMA
Other Organic Chemicals	4-tert-octulphenol, bisphenol-A	cholesterol, nonylphenol
Herbicides and Pesticides	Dalapon	Triclopyr
Pharmaceuticals and Personal Care Products	caffeine, DEET	Paracetamol, salicylic acid

2.3.5 Beaufort West Reclamation Plant

In response to severe water shortages, the Beaufort West Municipality made a decision to augment its existing water resources by reusing secondary-treated domestic sewage. The design of the reclamation plant was based on the multi-barrier concept, with the following barriers: Intermediate chlorination/rapid sand filtration, UF, RO, UV- H_2O_2, and final chlorination. Table 2.8 provides a summary of selected water quality determinands from the first year of operation. The final water complies with the SANS 241-1: 2011 (Edition 1) drinking water standard. Plans are in place to sample and analyse for EDCs in the near future and compare with results obtained by Umgeni Water's Darvill reclamation research project.

Table 2.8: Summary of Beaufort West Reclamation Plant Final Water Quality Results

Determinand	Unit	Sans 241-1:2011	Final Water (Mean)
Total Dissolved Solids	mg/l	<1200	34
Turbidity	mg/l	<1	0.2
Ammonia as N	mg/l	<1.5	<0.1
Nitrate and Nitrite as N	mg/l	<11.9	1.4
Faecal Coliforms	Count/100 ml	Not detected	0
E.coli	Count/100 ml	Not detected	0
DOC	mg/l	<10	<1.0

2.3.6 eThekwini Municipality Wastewater Reclamation

The eThekwini Municipality is investigating direct wastewater reclamation in order to maintain their assurance of supply, following rising water demand. Two direct reclamation options are being considered, based on the use of differing water treatment technologies. The two treatment technology trains are, in essence:

- a membrane-based treatment train; and
- an ozone/activated carbon treatment train.

The qualitative performance of the two selected reclamation treatment trains is reflected in Table 2.9. The ozone/granular activated carbon treatment train does not require costly brine treatment and disposal. This option therefore has advantages for use in inland-based reclamation schemes.

Table 2.9: Identified Treatment Barriers for Direct Reuse Treatment Technologies

Water quality variable category	Number of treatment barriers	
	Membrane based process	O3/GAC process
COD	CFC, MF/UF, NF/RO	CFC, BAC, GAC, UF
Particulate solids	CFC, MF/UF, NF/RO	CFC, GAC, UF
Nutrients: Nitrogen and Phosphorous	MF/UF, NF/RO CFC, MF/UF, NF/RO	UF CFC, UF
Microbiological	MF/UF, NF/RO, UV	O_3, UF, UV
Salinity, Inorganic	NF/RO	-
Metals	CFC, MF/UF, NF/RO	CFC, UF
Micro-organics	CFC, NF/RO, H_2O_2/UV	CFC,BAC,GAC, UV
Disinfection By-products	Not an issue	
Radionuclides	Not an issue	
Physical Quality	Not an issue	

2.3.7 Other Wastewater Reclamation Schemes

Wintgens et.al (2008) obtained data from three indirect reuse projects from around the world. Although the data is limited, the performance of the schemes and the various technologies used can be broadly compared in terms of their removal of certain organic contaminants (Table 2.10).

Table 2.10: Comparative Performance of Selected Reuse Schemes

Sample Point	Compound	Concentration ng/l
North City Water Reclamation Plant, San Diego (CA) – Advanced Water Treatment Pilot		
Tertiary effluent	Sulphamethoxazole	892
Reverse osmosis permeate	Sulphamethoxazole	2.9
UV & peroxide product	Sulphamethoxazole	<1.0
Bolivar Aquifer Storage and Recovery Scheme (South Australia)		
Reclaimed water	Estrone	32
Groundwater (5 month storage)	Estrone	24
Groundwater (11 month storage)	Estrone	11
Temporary Hanningfield reservoir augmentation by effluent from Chelmsford (UK)		
Sewage plant effluent	Estrone	833
UV-treated effluent	Estrone	1-20

2.4 EMERGING WATER RECLAMATION PROCESS CONFIGURATIONS

As technologies improve and monitoring equipment becomes more sophisticated it is anticipated that alternative process trains will be employed. Examples of some of the research being undertaken in this area are given in this section.

2.4.1 MBR-RO Systems

2.4.1.1 Toronto MBR-RO

A membrane bioreactor and reverse osmosis (MBR-RO) system was developed by the University of Toronto Department of Civil Engineering (Comerton, 2005) to assess potential reuse applications of municipal wastewater. The reuse water produced by the MBR-RO system meets California Title 22 water reuse regulations for non-potable applications and USEPA drinking water limits for trihalomethanes (THMs) (80 µg/l), haloacetic acids (60 µg/l), chlorite (1 mg/l), total coliforms (not detectable), viruses (not detectable), and nitrate (10 mg N/l). TOC, an indicator of DBP precursors, was effectively removed (93–100%) by the RO membranes, resulting in low TOC concentrations (< 1mg/l) in the RO permeate.

2.4.1.2 NEWater MBR-RO

Pilot testing at the NEWater Project has shown the MBR-RO option to produce a slightly superior quality product water than the conventional approach of secondary treatment followed by MF and RO, specifically with respect to TOC, nitrate and ammonia (Qin et al., 2009), and also tends to be lower cost (Judd, 2011).

The MBR-RO option was explored with trials of three MBR plants operating simultaneously. Comparison of the MBR-RO process to a conventional ASP-MF-RO process was also made. The MBR plants were fed with primary settled sewage having mean COD, ammonia, TKN and total phosphorous (TP) levels of 265, 33, 33 and 9 mg/l, respectively. The mean product water quality from each of the MBRs tested and MF permeate is given in Table 2.11.

Table 2.11: Comparison of Quality of NEWater MBR Product and MF Permeate

Parameter	MBR Product	MF Permeate
NH_4-N (mg/l)	0.05 – 0.62	0.97 – 2.57
NO_3 (mg/l)	17.6 – 22.8	25.2 – 42.2
TOC (mg/l)	4.9 – 5.1	6.8 – 6.9
pH	6.2 – 6.4	6.7 – 6.8

The results show that levels of NH_4-N, NO_3^- and TOC were lower in the MBR product than in the MF (0.1 µm PVDF hollow fiber) permeate from polishing of secondary effluent. It should be pointed out the better quality of the MBR product compared to the MF permeate was due to differences in the biological treatment efficiency of the MBR process as opposed to the physical separation process. RO membranes in the MBR-RO process could be operated at 22 $lm^{-2}h^{-1}$ without cleaning in place (CIP) during the whole five month study period, which was 30% higher than the rate (17 $lm^{-2}h^{-1}$) in the ASP-MF-RO process for NEWater production. With respect to the removal of organics in the RO permeates, the results showed that the TOC level of the RO permeate from the MBR-RO process was not only lower but also fluctuated less than the TOC level from the ASP-MF-RO process (Figure 2.1). The TOC level of the RO permeate from the ASP-MF-RO process fluctuated in the range of 33–53 ppb while the TOC level from the MBR-RO process was in the range of 24–33 ppb (Qin et al., 2009).

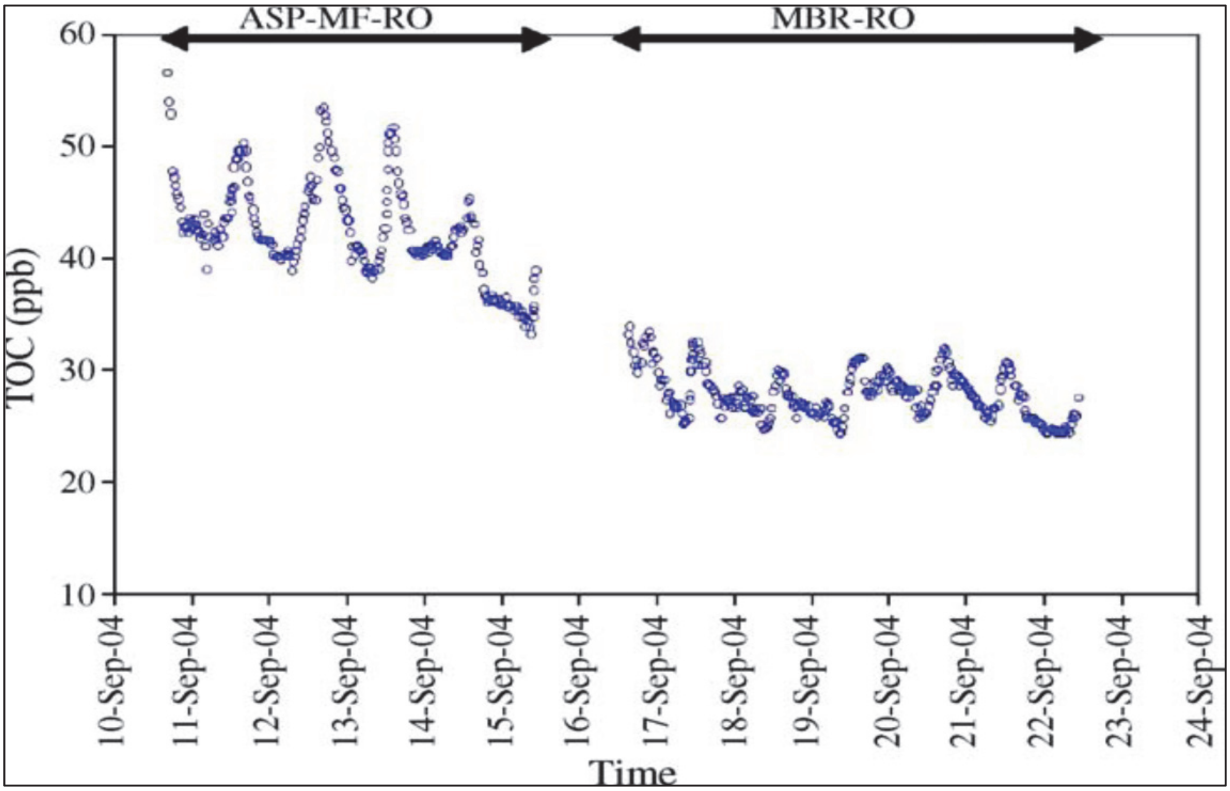


Figure 2.1: NEWater Pilot TOC comparison

2.4.2 Nanofiltration

One of the major problems with common DPR treatment schemes employing RO is the management of brine, especially in inland locations. To deal with this issue, a variety of advanced treatment processes are currently under development for the oxidation of trace organics, without the removal of dissolved solids (Leverenz et al., 2011). An example of such a system is shown in Figure 2.2. Another issue with schemes employing RO is the high energy usage required for treatment.

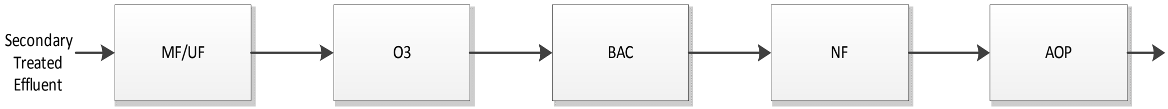


Figure 2.2: Alternative Advanced Treatment Flow Diagram with Trace Organics Removal

2.4.2.1 Nanofiltration and Ultra-Low Pressure Reverse Osmosis

Pilot testing has been undertaken to determine if low pressure membranes such as nanofiltration and ultra-low pressure reverse osmosis membranes can meet water quality requirements for indirect potable reuse. The results of the pilot suggest that ultra-low pressure RO and NF membranes can achieve similar removal efficiencies for the selected trace organics, nitrogen and bulk parameters tested as for commonly employed

RO membranes (Drewes et al., 2005). While providing a similar water quality, these membranes can be operated at significantly lower feed pressures. The two membranes selected for the laboratory-scale assessment (TMG10, Toray; NF-90, Dow-Filmtec) were employed on the pilot-scale skid for approximately 2,800 hours and 1,400 hours , respectively. Both membranes were capable of achieving a TOC ejection exceeding 98% with final permeate concentration of less than 0.3 mg/l.

The TMG10 (RO) membrane consistently achieved permeates with ammonia concentrations of less than 1.7 mg N/l, while the NF-90 permeate exhibited ammonia concentrations of less than 2.8 mg/l. While certain trace organics were present in the feed water, none of the pharmaceutical residues, chlorinated flame retardants and EDCs (hormones, bisphenol A) were quantifiable in the membrane permeates. Both membranes were operated at a flux of 20 lmh and a recovery of 85%. The temperature corrected specific flux of the TMG10 declined from 4.24 to 2.74 lmh/bar and the NF-90 declined from 6.49 to 2.74 lmh/bar after four weeks of operation. Both specific fluxes remained stable during the remainder of the test and were significantly higher than the specific flux of the Koch RO membrane employed at full scale which was operated at 2 lmh/bar.

2.5 PRODUCT WATER QUALITY OBJECTIVES

2.5.1 SANS 241

The product water quality objective is to exceed the potable drinking water standards of SANS 241 (2011). This is the standard that Umgeni Water uses for potable water production. However, because of the inherent risks in treating wastewater to potable standards, the water quality objectives set for this study are far stricter. An example of this would be TOC which has a standard of < 10 mg/l in SANS 241 (2011) but a target of < 1 mg/l in this study. Similarly, the SANS 241 (2011) standard for total coliforms is < 10 (CFU/100 ml), but in this study it is ND (not detectable). Additional water quality parameters such as trace organics were also measured. Concentrations of a number of human hormones and their derivatives were analysed: estrone, 17α-ethinyl estradiol, estriol, 17β-estradiol, testosterone and progesterone. The antibiotics, sulphamethoxazole and fluoroquinolones were also analysed.

Tests for these hormones and antibiotics have been carried out at wastewater reclamation schemes around the world such as at NEWater in Singapore and the Western Corridor Recycling Water Project in Australia. The concentration of these trace organics in the final reclaimed water from Darvill can thus be compared with these other reclamation schemes. The final potable water quality, prior to disinfection, should meet the following objectives, as laid out in Table 2.12, as well as additional standards for DBP and trace organics discussed below.

Table 2.12: Product Water Quality Objectives

Parameter	Specified/Design
SS Removal (NTU)	<0.5
Total Dissolved Solids (mg/l)	<100
Ammonia (mg/l)	<1
Total Nitrogen (mg/l)	<10
TOC (mg/l)	<1
UV_{254} (cm^{-1})*	0.065
Total Coliforms (CFU/100ml)	ND
Faecal Coliforms (CFU/100ml)	ND
Coliphages –Somatic (PFU/100ml)	ND
Pathogens Removal (%)	5-log (99.999%)
Silt Density Index $(SDI)_{15}$	<3

* New Goreangab

2.5.2 USEPA Regulations

USEPA has issued specific regulations regarding TOC in drinking water, i.e. the Disinfectants/Disinfection By-products Rule, D/DBPR (1st stage). Under this rule, utilities are required to remove predetermined amounts of TOC as a way to reduce DBP precursors and DBP formation. The required amount of TOC to be removed, as defined by the B/DBP rule, is affected by the raw water TOC concentration and raw water alkalinity (Table 2.13).

Table 2.13: Total Organic Carbon Removal Goals (USEPA)

TOC in raw water (mg/l)	TOC removal goals (%) for different raw water alkalinity levels (mg/l $CaCO_3$)		
	0-60 mg/l $CaCO_3$	60-120 mg/l $CaCO_3$	>120 mg/l $CaCO_3$
2.0-4.0	35	25	15
4.0-8.0	45	35	25
>8.0	50	40	30

The treatment goals and requirements are based on evaluations of DBP formation potentials, and on economic and practical reasons. USEPA's 2nd stage Disinfectants/Disinfection By-products Rule regulates two groups of disinfection by-products which originate from organic matter: total THMs, and a group of five haloacetic acids (HAA5). The maximum THM value of 80 µg/l is stricter than that in the EU Directive 98/83/EC, and the maximum value for HHA5 is 60 µg/l (Techneau, 2006). These standards are stricter than those used by SANS 241: 2011 and should be applied to any future reclamation plant, because of the higher risk of DBP potential formation as a result of the extensive use of advanced oxidation processes in wastewater reclamation.

2.5.3 Australian Guidelines

Table 2.14 presents calculated drinking water guidelines for trace organics and compares them with the highest concentrations measured in secondary-treated effluent in Australia. Given that this does not take into account reductions achieved by advanced treatment processes, it is unlikely that trace organics will be present at levels approaching the recommended drinking water guideline, or cause untoward effects in people drinking water from recycled water. Testing of recycled water produced at the Orange County Groundwater Replenishment Scheme and the Singapore NEWater scheme has not detected 17α-ethynylestradiol, estrone or 17β-estradiol. Nevertheless the guidelines can be used in South Africa as a safety benchmark for monitoring of trace organic concentrations in drinking water.

Table 2.14: Australian Drinking Water Guidelines

Pharmaceuticals	Maximum concentrations detected in wastewater (μg/l)	Drinking Water Guideline (μg/l)
Estrogenic compounds		
17α-estradiol	0.074	0.175
17β-estradiol	0.027	0.175
Progesterone	0.199	105
Estriol	0.051	0.05
Estrone	0.11	0.03
17α-ethinyl estradiol	0.270	0.0015
Androgenic compounds		
Testosterone	0.214	7
Androsterone	0.214	14

2.6 SUMMARY

The effectiveness of a range of water reclamation technologies such as membrane coupled (MBR) activated sludge treatment, membrane effluent filtration with porous and dense membrane processes, activated carbon adsorption as well as different oxidation processes (ozone, UV & ozone, UV & peroxide) has been investigated in a number of studies (Asano et al., 2006; Snyder et al., 2007). In reviewing the treatment trains presented in the case studies, it is apparent that a number of different unit processes have been employed for the removal of the constituents of concern in wastewater. What is evident is that each process produces a consistent water quality that is compliant with the regulations and drinking water standards in each country.

CHAPTER 3: WATER RECLAMATION PLANT PILOT TRIALS

3.1 INTRODUCTION

The successful schemes presented in Sections 2.3 and 2.4 provide a benchmark for the design of future indirect and direct potable reclamation schemes. Although similar, different schemes combine different technologies to achieve the same objective and it becomes difficult to justify a particular process train as the most suitable. When choosing a process train a number of factors need to be considered which include: feed water quality, capital and operating cost and final water quality. The work carried out as part of this study focused on identifying a treatment train that meets the following criteria:

- Achieves water of a quality that exceeds the national drinking water standard, SANS 241:1 2011;
- Adopts a multi-barrier approach and has two or more barriers per wastewater contaminant;
- Is the most economical process train that meets the water quality objectives.

3.2 TARGET TRACE ORGANIC CONTAMINANTS

Target compounds were selected from various classifications of trace organic contaminants. Classes considered included hormones, personal care products, pharmaceuticals and any other compounds that could be potential EDCs. Because of budget limitations only a small number of organic contaminants could be selected for analysis. The selection process was based on the following criteria:

- The likelihood of a chosen contaminant occurring in the in the environment should be great. A literature review of peer-reviewed journals, government reports and books provided information as to the prevalence of contaminants in the environment (Benotti et al., 2009; US Bureau of Reclamation, 2009; Kumar and Xagoraraki, 2010). This was necessary so that the performance of the advanced treatment processes in removing contaminants could be analysed.
- Availability of analytical standards.
- Indicator compounds that reflect the potential for contamination by other compounds, as well as the efficacy of a given type of treatment.

Benotti et.al. (2009) analysed source water, finished drinking water and distribution system tap water from 19 US water utilities for 51 CECs between 2006 and 2007. Both estrone and sulphamethoxazole were part of the 11 most frequently occurring compounds. Estrone was also identified as an indicator compound. Kumar and Xagoraraki, (2010) ranked CECs, in terms of priority, in four categories, namely: overall score, occurrence, ecological effects and health effects. Estrone, 17β-estradiol, 17α-ethinylestradiol, estriol and testosterone all ranked in the top twenty in varying categories.

The fluoroquinolone group of antibiotics (enrofloxacin and norfloxacin) and the antibiotic, sulphamethoxazole, also ranked in the top twenty. Fluoroquinolones represent classes of synthetic antibiotics that are widely used in human and veterinary medicine (Renew & Ching-Hua, 2004). Earlier studies show that these antibiotics are rather resistant to microbial degradation. Sulphamethoxazole has been among the top 200 drugs prescribed in the US from1995 to 2002. Based on the criteria above, the steroid hormones, 17-α-ethinylestradiol, 17β-estradiol, testosterone and progesterone, and two antibiotics, fluoroquinolones and sulphamethoxazole, were also chosen for testing.

3.3 DESCRIPTION OF SELECTED WATER RECLAMATION UNIT PROCESSES

Ozonation, GAC, NF, RO and UV radiation were tested in this project, due to their effectiveness. Three reclamation options were considered, based on the use of differing water treatment technologies and combinations thereof. The three treatment technology trains being considered are:

- A membrane-based treatment train (MBR-RO-UV);
- An ozone/activated carbon treatment train (MBR-O_3/GAC-NF-UV);
- An alternative treatment train (MBR-NF-O_3/GAC-UV).

The RO-based treatment train can to a large degree be considered a replica of the NEWater process i.e. MF/UF-RO-UV, while the ozone/activated carbon treatment train combines major components of the Goreangab wastewater reclamation plant process. Work done by Qin et al. (2009) at NEWater showed that the MBR-RO treatment combination produced high quality water. There are advantages and disadvantages to both processes, which will be evaluated during the bench-scale testing. The use of NF as an alternative to RO, particularly in combination with MBR, will also be evaluated as it has potential advantages over RO as reported by Wintgens et al. (2008).

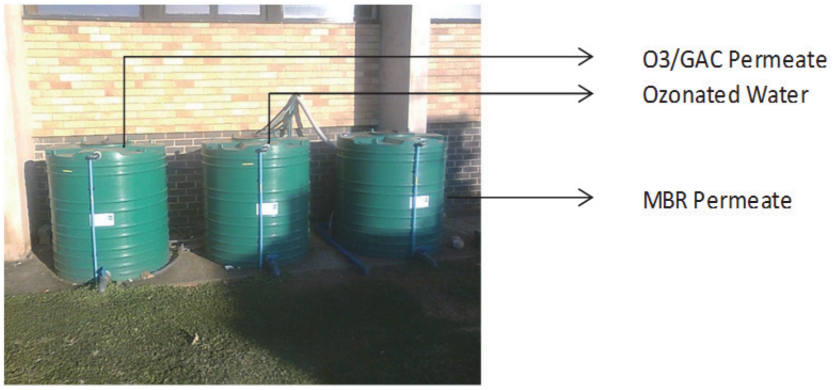
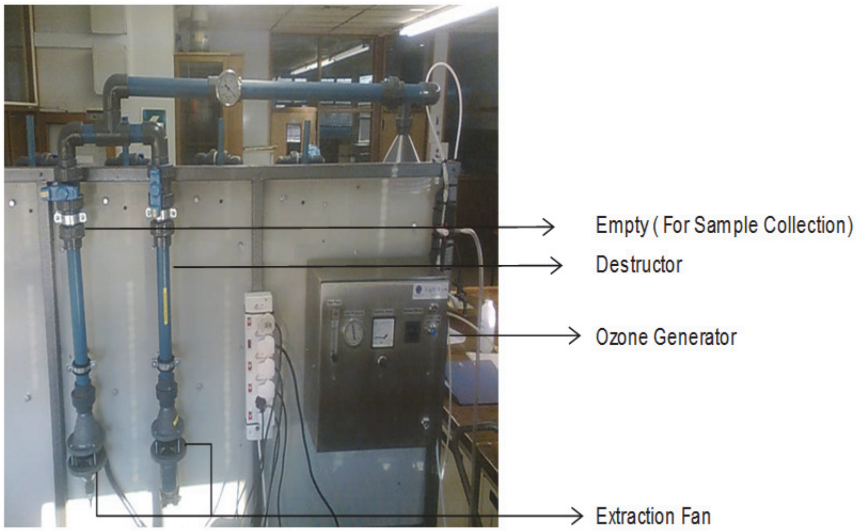
3.4 MEMBRANE BIOREACTOR SYSTEM

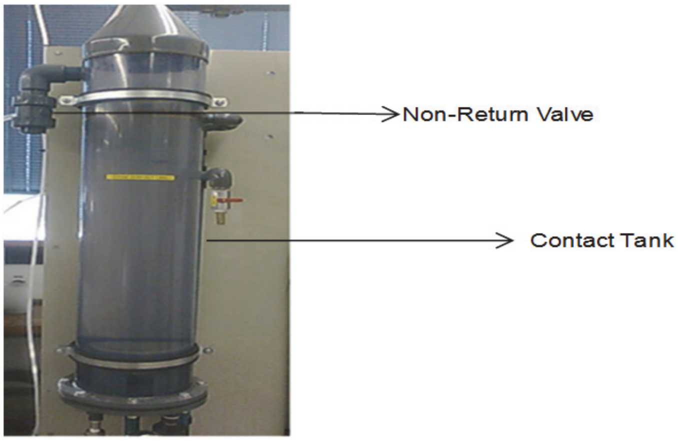
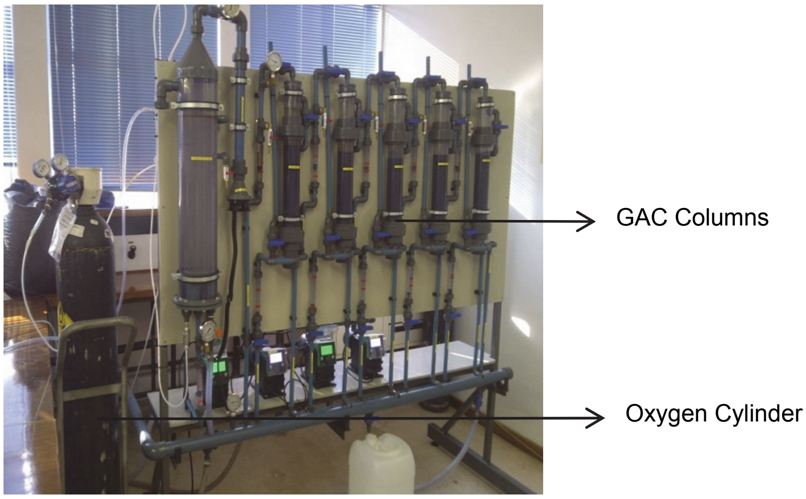
In all configurations, the Toray MBR demonstration plant was used as a pre-treatment step, after it proved to be the most reliable and easy to operate of the pilot plants tested in the early part of the study, as reported in Volume 1.

3.5 THE MBR-OZONE/GAC TREATMENT SYSTEM

3.5.1 Description of the MBR-Ozone/GAC System

The MBR-ozone/GAC treatment step was set up first as this system could be operated before the membrane units were installed. The MBR-ozone/GAC treatment process is also a continuous process and therefore lends itself to a greater volume of (daily) records. The GAC was operated with the understanding that with time a biofilm would form on the carbon and the unit would operate as a BAC. In addition, the addition of ozone upstream of the GAC unit would enhance the conversion to a BAC by breaking down organic matter in the feedwater into more readily biodegradable substances that are a food source for the developing biofilm. The ozone/GAC system consists of the following components (Figures 3.1–3.4):

Three (1,000 l) holding tanks	 **Figure 3.1: Holding Tanks**
Ozone generator	 **Figure 3.2: Ozone Generator**

Ozone contact column	 **Figure 3.3: Ozone Contact Column**
Five GAC packed columns • Oxygen cylinder • Two extraction fans: The first has a destructor used for residual ozone removal (Carulite 200 Granular Catalyst) and the second is for sampling the gaseous residual ozone.	 **Figure 3.4: GAC Packed Columns**

Additional components of the ozone/GAC unit are listed below and are illustrated in the process flow diagrams in Annexure B-B:

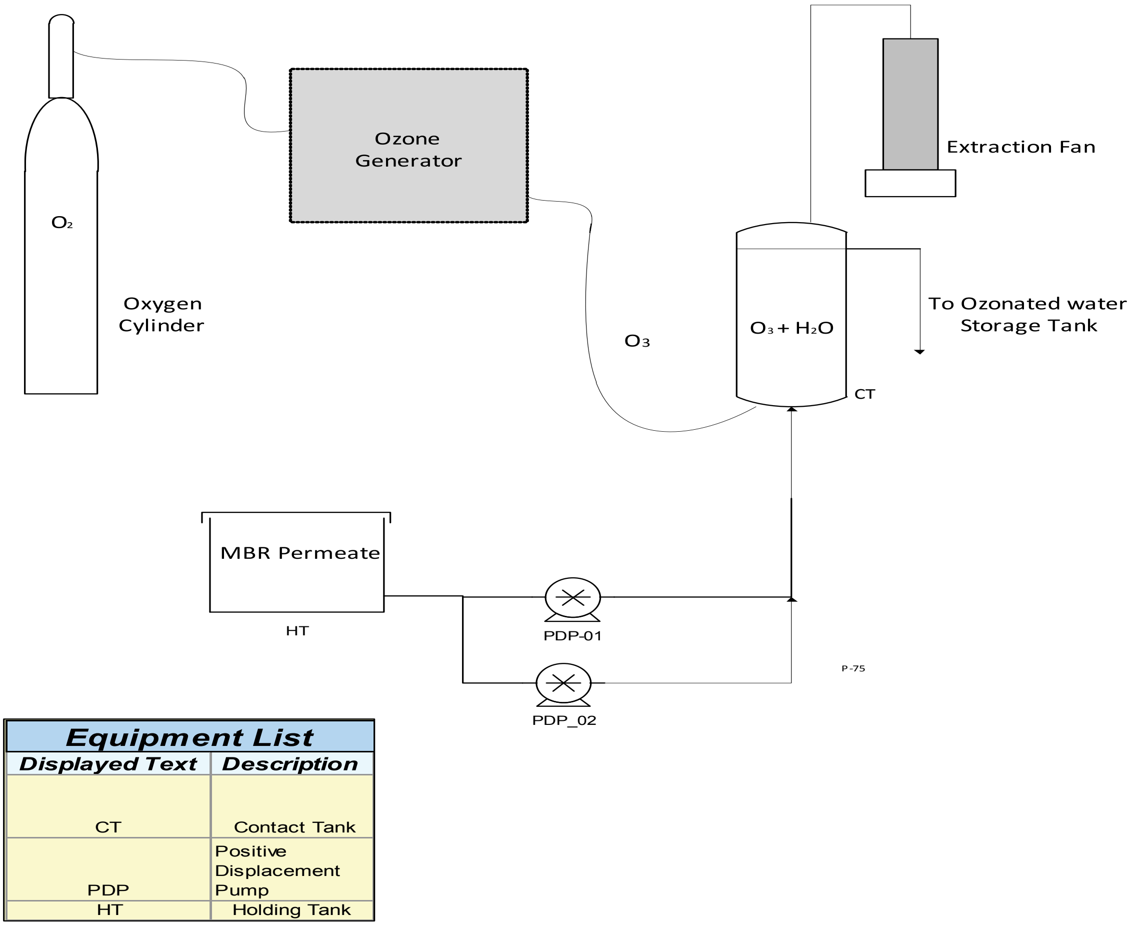
- MBR permeate tank outlet valve
- Inlet and outlet ball valves for each GAC column
- Flow metres on the inlet of every GAC column
- Four positive displacement pumps (max. flow of 30 l/h)
- Backwash ball valves at the bottom of each column
- Two pressure gauges on the GAC section, one for the pressure across the columns and the other for the backwash stream
- Sample points for each column excluding the fifth one
- Flow meter on the ozone contact tank inlet
- Contact tank inlet and outlet ball valves
- Non-return valve on the ozone contact tank

- Two pressure gauges on the ozonation section; one on the water feed line to the contact tank, and the other mounted on the pipeline that transfers residual ozone from the contact tank to the extraction fan
- A sample point on the ozone contact tank outlet
- Multiplug for pump and fan connections.

3.5.2 Experimental Methodology

3.5.2.1 Ozonation

The MBR permeate was fed to a 1,000 l holding tank. From the holding tank the water is pumped by positive displacement pumps at 0.3 bar producing a flow of 24 l/h to the ozone contact tank, where it comes into contact with ozone flowing at 0.216 g/h from the ozone generator. The ozone generator uses oxygen to generate ozone. An oxygen cylinder is used to supply the ozone generator with oxygen at a supply pressure of 0.5 bar. The contact tank has a volume of 10 l which allows for a sufficient contact time of 25 minutes. The ozonated water from the contact tank is fed to the ozonated water holding tank *(F*igure 3.5). The required ozone dose was calculated as 9 mg/l (see annexure B-C), for an ozone demand of 5 mg/l based on a residual ozone concentration of 0.23 mg/l.

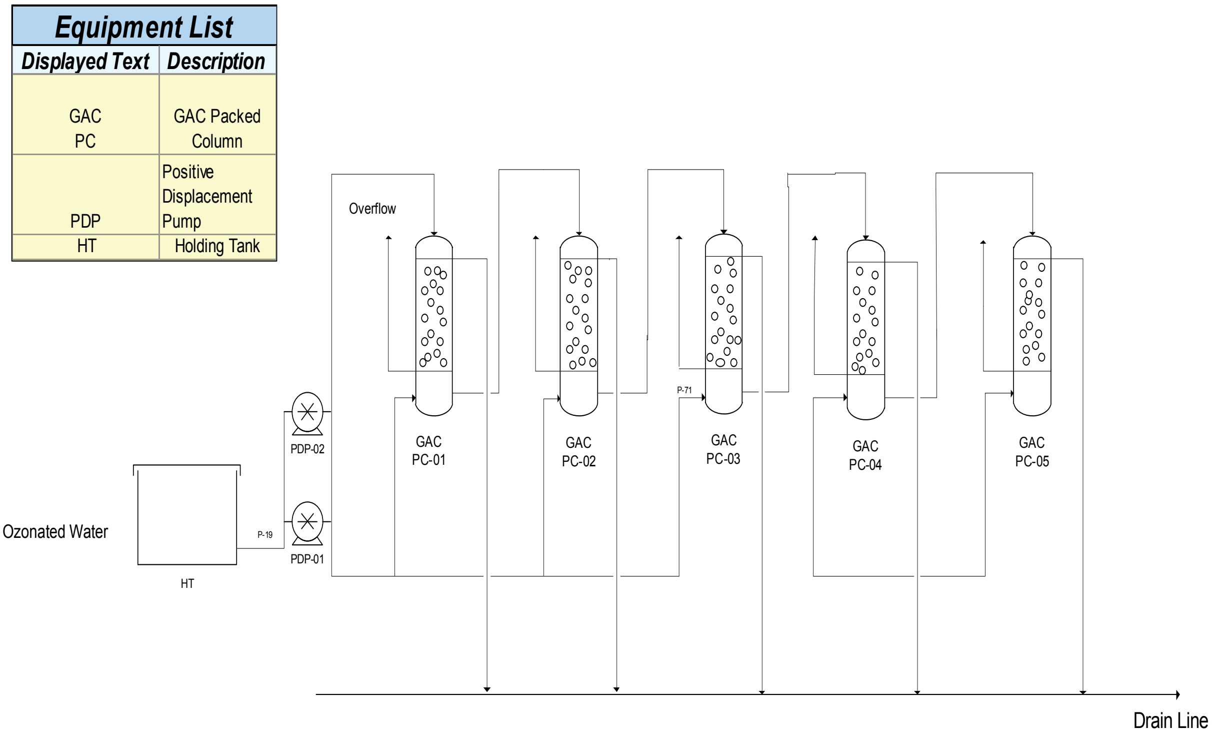


Equipment List	
Displayed Text	**Description**
CT	Contact Tank
PDP	Positive Displacement Pump
HT	Holding Tank

Figure 3.5: Ozonation Schematic

3.5.2.2 *Granular Activated Carbon filtration*

The water from the ozonated water holding tank was pumped by a positive displacement pump at 0.3 bar to a series of five GAC columns. The feed water flow was 24 l/h and the hydraulic loading rate was 6.24 m/hr. The EBCT is 2.9 min per column or approximately 15 min in total. The filtered water from the GAC columns is fed to the Ozone/GAC treated water holding tank (GAC filtrate tank). During backwash, the treated water is fed to the bottom of each column removing the contaminants from the GAC and the contaminated water is discharged via the drain line (Figure 3.6*)*.



Equipment List

Displayed Text	Description
GAC PC	GAC Packed Column
PDP	Positive Displacement Pump
HT	Holding Tank

Figure 3.6: Granular Activated Carbon Filtration Schematic

3.6 THE MBR-O_3/GAC-NF/RO-UV TREATMENT SYSTEM

The MBR-Ozone/GAC treatment process provided the feedwater for the downstream NF and RO membrane units.

3.6.1 Membrane Modules and Properties

Six commercially available NF membranes and four RO membranes were used in this phase of the study. These membranes were kindly supplied as flat sheets by Dow Filmtec, Toray and Hydranautics. All membranes were immersed in deionised water and stored in darkness at 4 ^{o}C. Tables 3.1 and 3.2 show some of the main characteristics of NF and RO flat sheet membranes, respectively. NF 90 is a thin-film composite membrane with a fully aromatic cross-linked polyamide layer. It was developed by Dow Filmtec in order to have a high salt retention, i.e. NF 90 rejects at least 95% $MgSO_4$. NF 270 is composed of a cross-linked semi-aromatic piperazine-based polyamide layer on top of a polysulfone micro-porous support, reinforced with a polyester non-woven backing layer. The use of piperazine stems from the fact that polyamide membranes comprised of secondary amines, such as piperazine, have a higher stability against hypochlorous acid and other oxidizing agents. The membrane is very hydrophilic (it has a low contact angle), and it has a high negative surface charge at pH > 4, leading to a strong repulsion of negatively charged species.

Table 3.1: NF Flat Sheet Membrane Characteristics

Membrane	**NF-90**	**NF-270**	**ESNA1-LF2**	**UTC-60**	**Nano SW**	**SR-90**
Manufacturer	Dow Filmtec	Dow Filmtec	Hydranautics	Toray	Hydranautics	Dow Filmtec
Composition top layer	Cross-linked, fully aromatic polyamide.	Cross-linked, semi-aromatic, piperazine-based polyamide,	Aromatic polyamide	Polypiperazine amide	Composite polyamide	Negatively charged
MWCO (g mol^{-1})	100	155, 170, 200-300		150		
Pore size (nm)	0.38	0.48	0.30			
Membrane roughness	40.0	4.38	55.0	13.9		
pH range	2-11	3-10	2-10	3-9		
Water permeability (lmh/bar)		15.8	7.6		15.53	
Contact angle (^{o}) (sessile drop method)	54, 44.7	29, 27, 32.6	55	51.6		

Table 3.2: RO Flat Sheet Membrane Characteristics

Membrane	**UTC70B**	**UTC70UB**	**LFC3**	**XLE**
Manufacturer	Toray	Toray	Hydranautics	Dow Filmtec
Composition top layer	Polysulfone-polyamide	Polysulfone-polyamide	Composite Polyamide Neutrally charged	Polyamide Thin-film Composite
pH range	2-11		2-10	2-11
Water permeability (lmh/bar)	7.2		9.32	7.8
Contact angle (^{0}) (sessile drop method)	54			40
Salt rejection (%)	97.2	99		99
Retention NaCl (%)	99.4			98

3.6.2 Experimental Methodology

3.6.2.1 Cross-Flow Experiments

A laboratory-scale cross-flow NF and RO set-up was used in this study, as schematically shown in Figure 3.7 and pictured in Figure 3.8. The set-up comprised a PVC plate-and-frame membrane cell (Figure 3.9), which had membrane channel dimensions of 80 mm in length and 30 mm in width, with an effective surface area of 25 cm^2, a 50 l HDPE feed tank, and a Hydra-Cell Model DG 10 high pressure feed pump. The module was fed from a common pressurized feed solution obtained after the GAC filtration step of the process train. The feed concentration was kept constant by recirculating both concentrate and permeates into the feed tank. Permeate flow rate was captured by measuring volume collected within two minutes, using a measuring cylinder, while the retentate flow rate was monitored by a rotameter. Feed pressure and cross-flow velocity were controlled by means of a bypass needle valve and a back pressure regulator.

All filtration experiments were run at a cross-flow rate of 30 l/h, which translates to a cross-flow velocity of 0.08 m/s. The feed solution was kept at a constant temperature of 20 (±0.5) °C, controlled by a circulating heater/chiller. Pressure was also held constant at 10 bars, except where it was the variable to be examined. At the beginning of every experiment, the membrane pieces were pre-compacted with pure water under a constant pressure of 10 bars until permeate flux stabilized. Permeate quality in terms of key pollutants composition, and flux decline caused by fouling, were selected as response parameters. Turbidity, conductivity, microbial content (coliphages, coliforms and *E.coli*), TOC, alkalinity and nitrates were measured in the feed and permeate side of each membrane.

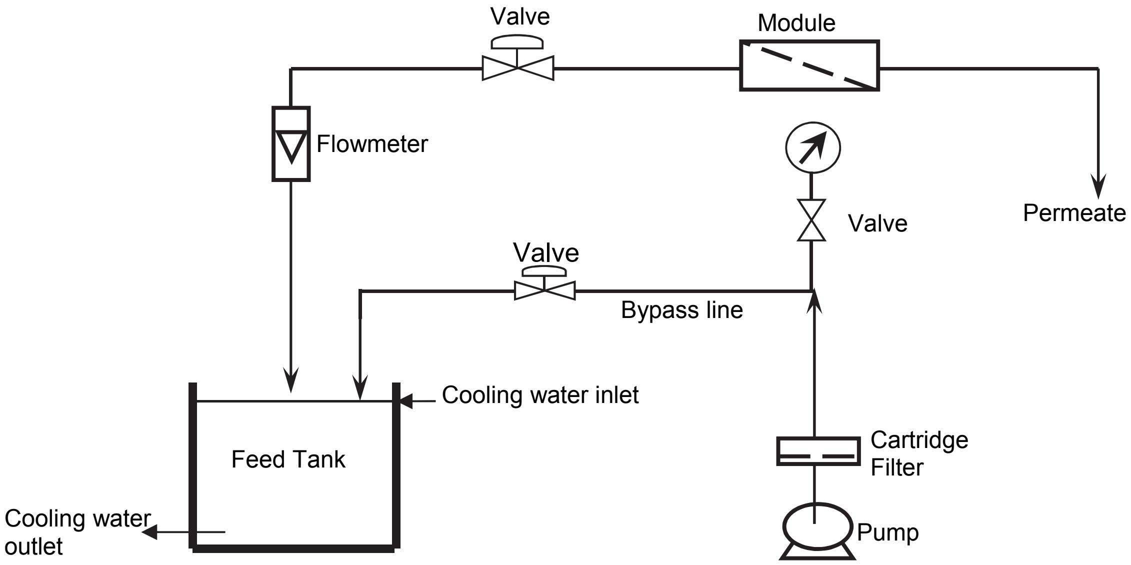


Figure 3.7: Schematic of Laboratory-scale Membrane Unit

Figure 3.8: Membrane Test Unit

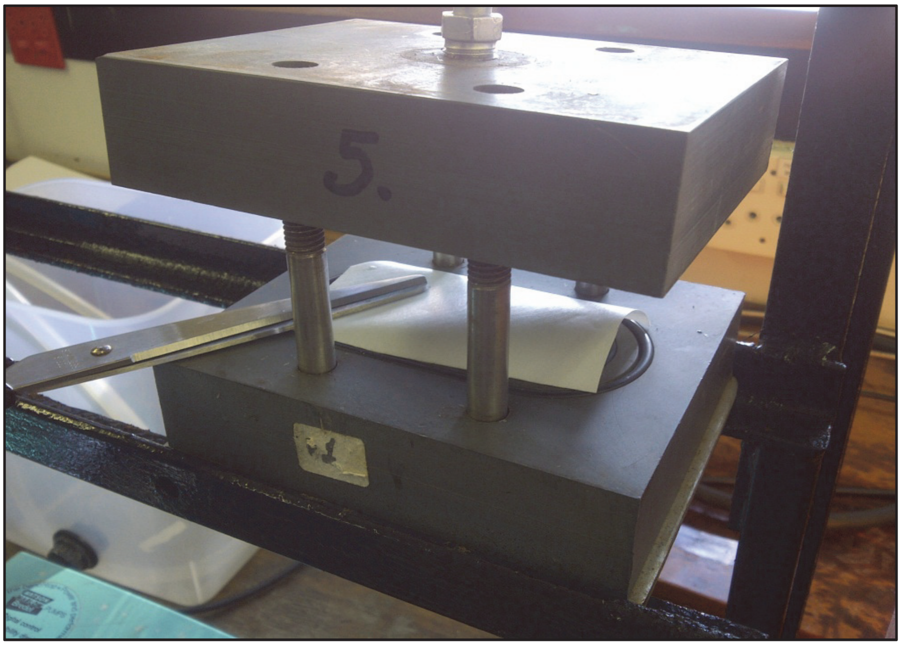


Figure 3.9: uPVC Membrane Module

3.6.2.2 Continuous Flow Experiments

A two stage membrane test rig was employed for the continuous flow experiments. The membrane unit employed two single element (2540 spiral wound) vessels arranged in a two stage array. The rigs were fully contained and portable, each consisting of a feed vane pump (max 15 bar pressure) and two cartridge filters (5 µm) in series for the pre-treatment system (see Figure 3.10). The rigs can be plugged into any standard 220 V power supply. Spiral wound RO membranes were then requested from membrane suppliers for comparative testing. Spiral wound RO membranes were generously donated by Toray (TR702540HF and FR702540) and Dow Filmtec (XLE2521). The RO test rigs were run in parallel to ensure a representative feed to each membrane. The feed to the test rigs was either from the MBR permeate tank or from the O_3/GAC permeate tank. The RO permeate from individual test rigs was then captured and fed as a batch process to the UV radiation unit. The UV unit process could not be run continuously with the RO test rigs because of a mismatch in the flow rates. The UV unit has a far greater flow rate (4 m^3/h) than the RO test rig (1 m^3/h).

Figure 3.10: RO Membrane Test Rigs Operating in Parallel

No chemicals were used upstream of the NF and RO membranes to adjust pH or as an antiscalant. For the continuous flow NF and RO spiral wound experiments, the Silt Density Index (SDI) was measured after the MBR and GAC units and before the NF and RO membranes. The SDI was consistently at an SDI < 3, which was within the manufacturer's specification.

3.7 THE MBR-RO-UV/H_2O_2 TREATMENT SYSTEM

UV pilot tests were conducted on pre-treated (MBR-RO) waste water. The feed water quality during the different tests is shown in Table 3.3.

Table 3.3: Feed Water Quality from MBR-RO Treatment Train

Date	pH	TOC	TDS	Turbidity
25-10-12	7.05	0.82	197	0.49
26-10-12	7.81	0.81	174	0.39

3.7.1 Description of the UV/H_2O_2 Unit

The stainless steel pilot UV unit (200–4000 l/h) was equipped with between three and ten Hg lamps (Figures 3.11 and 3.12). The power of each lamp is 100 W and the UV intensity is 26 mJcm^{-2}.

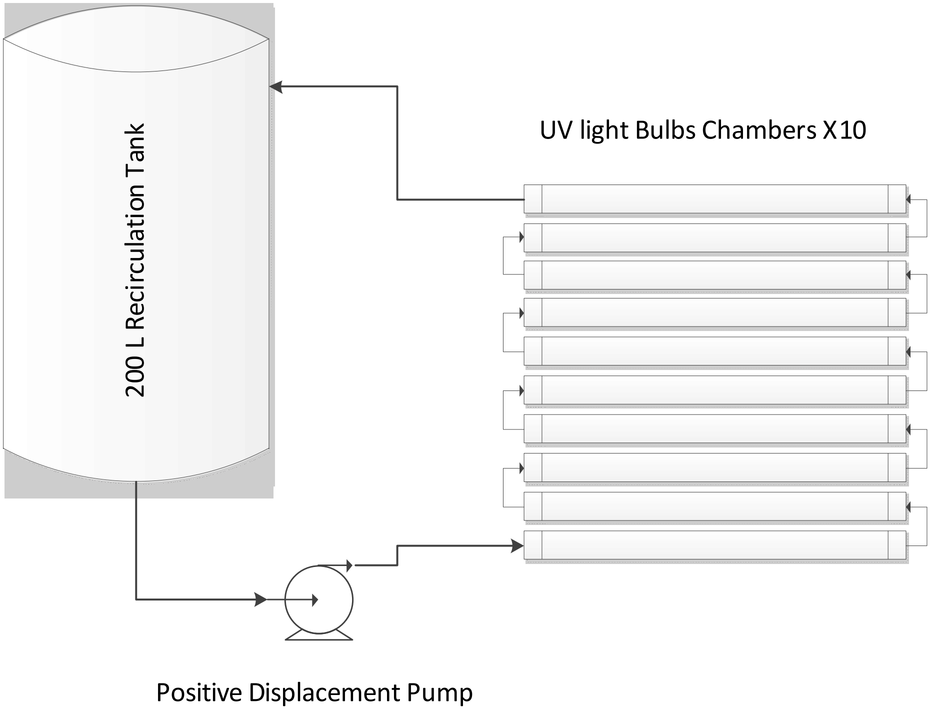


Figure 3.11: Schematic Depiction of the Pilot UV Unit

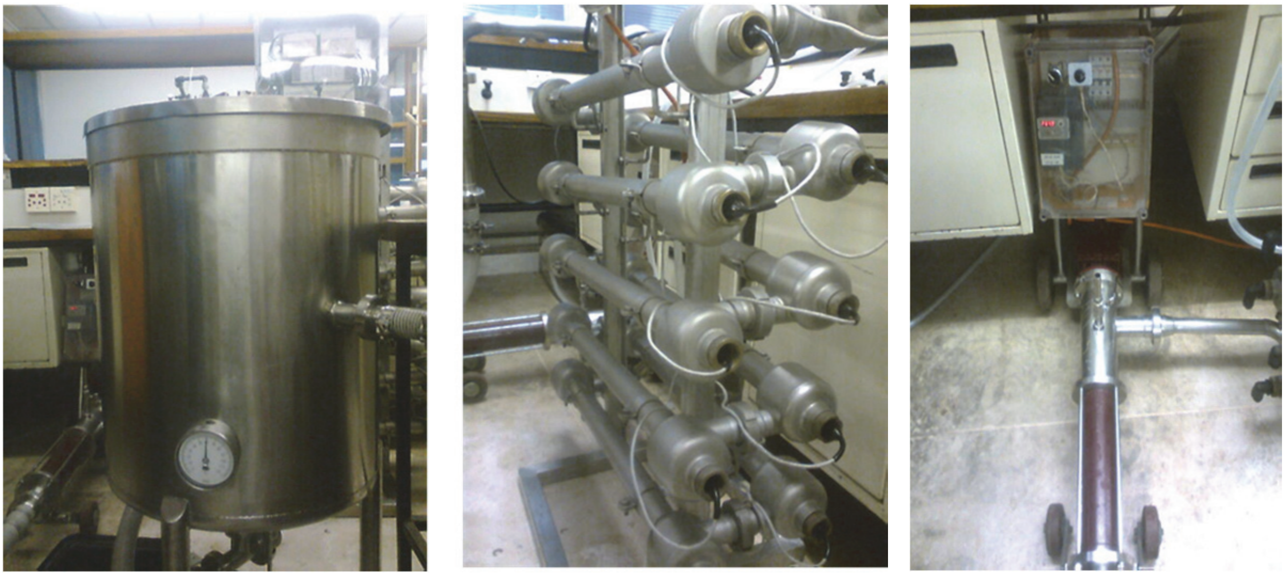


Figure 3.12: UV Pilot Unit showing: Recirculation Feed Tank, UV Lamps (x10) and Pump

3.7.2 Experimental Methodology

Testing for the effect of UV/H_2O_2 was carried out by testing the UV absorbance of the water after each process, using a UV spectrophotometer. The UV tests were done at different wavelengths for analysis of different organic content.

- Absorption at the following wavelengths was performed:
  - UV_{210} – enables detection of most of the organic compounds such as aldehydes, carboxylic acids, esters and nitrites.
  - UV_{254} – is characteristic of aromatic molecules.
  - UV_{280} – is mainly used to detect proteins.
- Reagents
  - Laboratory grade reagents were used: H_2O_2 (50%).
- Flow through experiments – UV radiation unit.

H_2O_2 was dosed to water in the recirculation tank to the UV/H_2O_2-pilot unit (as shown in Figures 3.11 and 3.12). For the first set of tests the water was passed through the UV unit without addition of H_2O_2 and then different concentrations of H_2O_2 were added for optimisation purposes. Samples were collected at 30 minute intervals for both experiments, for studying the behaviour of the processes with time.

3.8 SAMPLING AND SAMPLE PREPARATION

3.8.1 Sampling

Three sets of grab samples were collected from sampling points. Grab samples were collected, as opposed to composite samples, since the study focuses on treatment process efficiency and not on pollutant loads. Moreover, the balancing tanks allow a steady flow rate along the advanced treatment train and variations in water quality were not expected to occur while sampling. For TOC analysis, samples were collected into 2 litre plastic bottles, as well as 500 ml bacto bottles (containing 1% sodium thiosulphate to prevent reactions occurring) for microbial analysis. All bottles were rinsed three times with the water to be sampled before filling.

The EDC sample collection was as per the recommended procedure (Swart and Pool, 2007). Glass bottles (250 ml) were sequentially: washed with detergent, rinsed with running tap water, rinsed four times with distilled water and finally rinsed with 25 ml HPLC grade ethanol (99.5% purity, from Merck). The inverted bottles and caps were allowed to dry on a drying rack. The head of the bottle was covered with foil before the cap was screwed on. In the absence of amber bottles, the clear glass was covered with foil. Collected water can be stored for 3 days at 4 ^{o}C. No additions to the sample were required. The samples, packed with ice packs in a cooler box and protected from light, were couriered the same day to the testing laboratory. On arrival, they were stored at 4 ^{o}C prior to analysis (which occurred within a week). A list of the analytical instrumentation used by Umgeni Water in their Burger Street head office laboratory is provided in annexure B-D.

3.8.2 EDCs – Preparation of the Stock Standard

17-α-ethinylestradiol, estrone and testosterone were purchased from Sigma-Aldrich (via local agents, Capital Lab Supplies). The purity of the EDCs was ≥ 98% for 17-α-ethinylestradiol, ≥ 99% for estrone and ≥ 99% for testosterone. The solvent dimethyl sulfoxide (DMSO) was purchased from Radchem Laboratory Suppliers with ≥ 99.5 % purity.

3.8.2.1 EDC Stock Standard (20 mg/l)

Table 3.4: Preparation of 20 mg/l EDC Stock Standard

Reagent	Mass
17-α-Ethinylestradiol	0.0058g
Estrone	0.0056g
Testosterone	0.0051g

Each of these reagents was dissolved in a 250 ml volumetric flask using DMSO by sonication and stored in a cold room at ± 4 ºC. Each standard was prepared fresh at least every month.

3.8.2.2 EDC Intermediate Standard (20,000 ng/l)

The standard was prepared by placing 0.5 ml of the stock standard into a 500 ml volumetric flask. The volume was made up to the mark with ultrapure water.

3.8.2.3 EDC Spiking Standard

EDC spiking standard solutions were made by placing known volumes of the stock solution in 500 ml volumetric flasks, to make up the required spiking solutions (see Table 3.5).

Table 3.5: Preparation of the EDC Spiking Standard

Volume in ml	Concentration ng/l
0.25	10
3.75	150
50.0	2000

3.8.3 Analytical Method for Assay: ELISA

Samples were sent to the University of the Western Cape (UWC) for analysis using the enzyme-linked immunosorbent assay (ELISA) technique. The methods used for extracting and assaying environmental water samples for estrogenic compounds are described in detail in the paper by Swart and Pool (2007). These tests were extensively validated using spiked, real water samples and the standards provided in the commercial kits. For estrone, the recovery averaged, over the range 15–

2000 ng/l, 102.5 (± 5.7)%. Intra-assay and inter-assay variation was 5.5 (± 0.3)% and 8.2 (± 0.7)% respectively. For estradiol, the recovery averaged, over the range 25–2000 ng/l, 95.8 (± 9.0)%. Intra-assay and inter-assay variation was 8.9 (± 1.0)% and 3.9 (± 0.1)%, respectively. Samples were assayed for estradiol and estrone by ELISA, using the estradiol ELISA kit (cat. No. RE52041 IBL, Germany) and the estrone ELISA kit (Cat. No. DB 52051 IBL, Germany). The detection limits for both these estrogens are 1 ng/l.

3.8.4 Liquid Chromatography – Organic Carbon Detection (LC-OCD)

Samples were also sent to Germany after each unit process, for identification of the carbon molecular weight distribution. A very sensitive separation technique known as liquid chromatography – organic carbon detection (LC-OCD) was used. Separation is based on size-exclusion chromatography (SEC) followed by multi-detection with organic carbon (OCD), UV-absorbance at 254 nm (UVD) and organic bound nitrogen (OND).

CHAPTER 4: RESULTS AND DISCUSSION

4.1 INTRODUCTION

The MBR-Ozone/GAC treatment process provided the feedwater for the downstream NF and RO membrane cells. The MBR-Ozone/GAC treatment step was analysed separately at first as this system was operational before the membrane units were installed. The MBR-ozone/GAC treatment process is also a continuous process and therefore lends itself to a greater volume of (daily) records.

The membrane test units were operated as a batch process which requires regular supervision and the extraction of permeate is slow and time consuming. Results from the membrane units are therefore not as readily available. Twelve months (April 2012 to April 2013) of almost continuous data is available for the MBR-Ozone/GAC treatment process. The GAC was operated with the understanding that with time a biofilm would form on the carbon and the unit would operate as a BAC. The addition of ozone upstream of the GAC unit would enhance the conversion to a BAC by breaking down organic matter in the feedwater into more readily biodegradable substances that are a food source for the developing biofilm.

It has been reported (Wang et al., 1995 & Liu et al., 2001) that achieving steady-state biological removal of organic matter does not take as long as steady-state biofilm formation. The amount of biofilm and the removal of organic matter do not necessarily correlate. Servais et al. (1994) observed that pilot-scale GAC filters require 100 days before steady-state removal has been achieved, but Liu et al. (2001) reported time periods of 20 to 40 days for GAC-sand bio-filters to reach (pseudo) steady-state removal at 20 °C.

4.2 PERFORMANCE OF THE MBR-OZONE/GAC TREATMENT SYSTEM

4.2.1 Water Quality Results

The water quality results for samples taken after MBR, ozonation and GAC unit treatment are 37tabilizat in Table 4.1. The experimental results obtained confirm the efficiency of ozone for wastewater disinfection. A 93% reduction in average coliform concentration from the MBR feed was achieved. Faecal coliforms where reduced to zero after ozonation. The performance of ozone disinfection was enhanced by the quality of the feed water from the MBR, which has very low suspended solids, less than 4 mg/l.

Lazarova et al. (2013) showed that the quality of the effluent impacts on the effectiveness of ozonation and the dosage requirements. To achieve a 2-log reduction of faecal coliforms the required ozone dosage varies between 2 and 3 mg/l for tertiary effluents, 6 and 17 mg/l for secondary effluents, and up to between 25 and 30 mg/l for primary effluents. It was observed that with the decrease of effluent quality (increase of TSS, COD); the dispersion of experimental results strongly increases.

Table 4.1: Summary of MBR-Ozone /GAC Water Quality Results

MBR-O_3-GAC		MBR Out				O3 Out				GAC Out			
	Units	Mean	Median	STD	95%	Mean	Median	STD	95%	Mean	Median	STD	95%
Alkalinity	mE/l	122.89	125.50	36.23	178.75	127.44	125.00	41.39	197.40	115.59	121.00	47.88	190.20
Coliforms	CFU/100ml	44.48	5.00	114.29	181.55	2.81	0.00	8.18	25.95	123.08	2.00	431.83	477.40
Coliphages	PFU/100ml	5.60	0.00	25.77	13.35	0.08	0.00	0.44	0.00	0.02	0.00	0.14	0.00
EC	mS/m	67.31	66.00	8.15	82.36	68.73	67.35	9.64	86.88	69.45	66.85	9.51	86.26
E. Coli	CFU/100ml	9.59	0.00	40.26	17.50	0.04	0.00	0.19	0.00	0.04	0.00	0.19	0.00
NH_3	mg/l	0.50	0.50	0.01	0.50	1.73	0.50	3.89	12.28	1.32	0.50	2.96	9.49
NO_3	mg/l	9.51	8.28	5.27	19.52	9.21	8.03	5.21	18.93	9.66	8.32	5.04	19.02
TKN	mg/l	3.03	3.00	0.28	3.00	3.02	3.00	0.13	3.00	3.00	3.00	0.00	3.00
SRP	µg P/l	1.80	0.66	2.16	6.12	1.64	0.59	1.97	5.89	1.42	0.23	1.95	5.84
TP	µg P/l	2.03	0.60	2.31	5.99	1.61	0.50	1.86	5.48	1.49	0.50	1.81	5.50
TOC	mg/l	8.61	8.56	1.61	10.81	7.39	7.30	1.60	9.85	5.15	5.04	1.68	7.81
Turbidity	mg/l	0.32	0.27	0.18	0.77	0.39	0.21	1.26	0.69	0.25	0.21	0.12	0.50
pH	mg/l	7.45	7.44	0.24	7.80	7.58	7.58	0.39	7.88	7.50	7.48	0.20	7.78
TDS	mg/l	275.77	245.00	162.94	554.40	210.65	148.50	129.30	451.25	204.73	152.50	140.86	494.00

These results from Lazarova et al. (2013) clearly demonstrate the need for tertiary filtration, not only in order to decrease ozone dosage requirements, but also to consistently meet stringent regulations, avoiding the shielding impact of suspended solids, which can greatly influence the residual coliform concentration.

The water quality results were good, with some exceptions. The median results after the GAC process were 0.21 NTU for turbidity, 0.5 mg/l for total phosphorous (TP) and 5.0 mg/l for total organic carbon (TOC). Pathogen removal was excellent with median E.coli results of zero CFU/100ml and median coliphage results of zero PFU/100ml.

Graphical representations of some of the monitored determinands are given in Figures 4.1 to 4.3, and are discussed in the sections which follow. The coliform results were unexpectedly high (477 CFU/100ml at the 95th percentile), which may be a result of breakthrough of microbiological growth associated with GAC fines released from the filter medium. A major concern with the use of GAC filters optimised for microbiological growth is the potential introduction of microorganisms to the distribution system in this way (Morin et al., 1996). Carbon fines with large surface areas would be able to carry bacteria and to optimise the colonisation of the biofilms by the coliforms they transport. The protection conveyed to bacterial cells by their attached state may allow them to pass through the disinfection barrier (LeChevallier, 1990) without being severely injured and therefore to reach the biofilm under conditions that may increase their capacity for colonisation (Morin et al., 1996). Nitrate levels are high with average values of 9.5 mg/l and 19.5 mg/l at the 95th percentile in the MBR permeate. As ozonation and GAC are not expected to remove nitrate these values stay relatively constant throughout the process. These high nitrate values are indicative of a poor denitrification process in the anoxic zone of the Toray pilot plant. The biological process suffers from the lack of an effective anoxic zone.

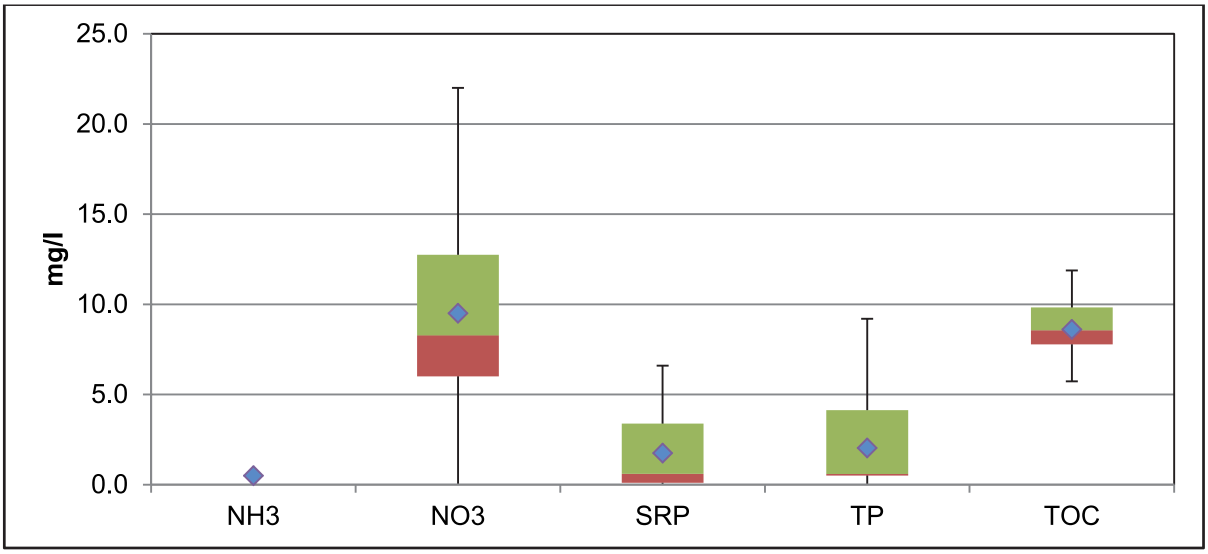


Figure 4.1: MBR Permeate (May–Nov 2012)

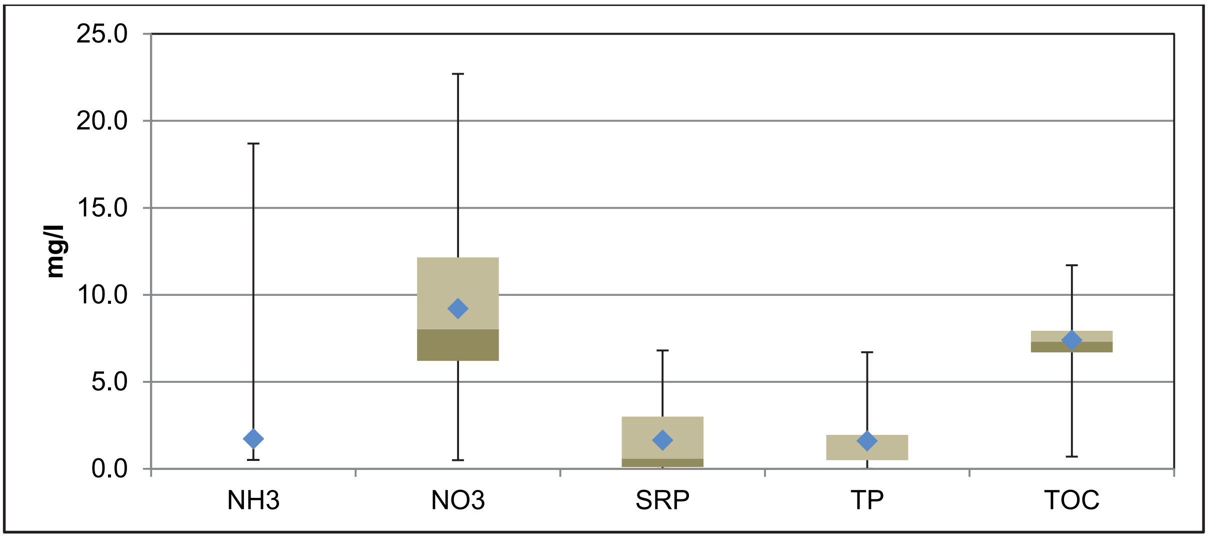


Figure 4.2: Ozonation Permeate (May–Nov 2012)

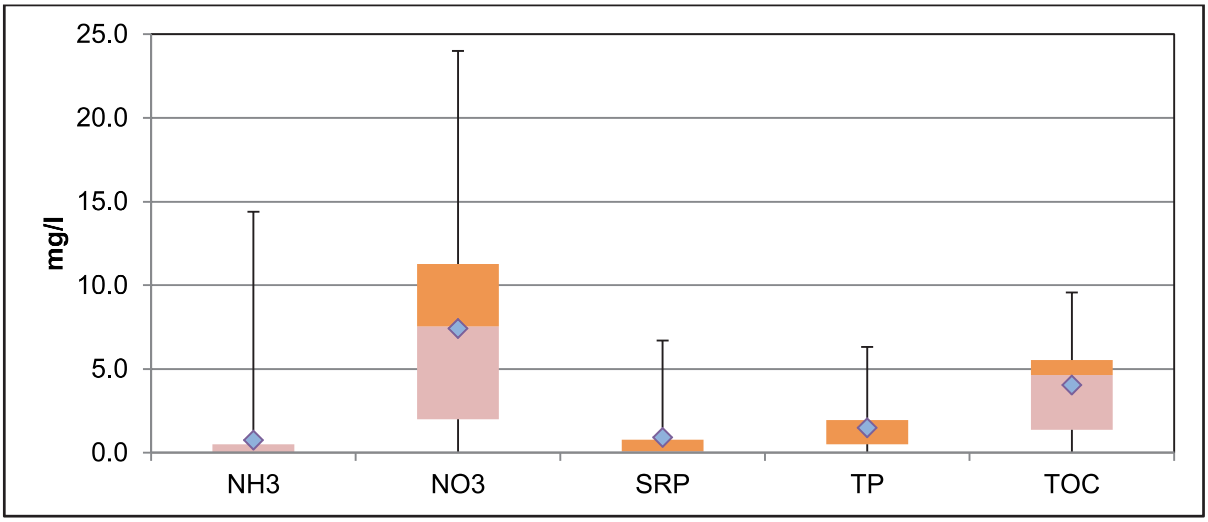


Figure 4.3: GAC Permeate (May–Nov 2012)

4.2.2 Ammonia (NH_3) and Nitrate (NO_3)

Figure 4.1 illustrates that ammonia is being effectively removed by the activated sludge process and in the MBR process, through nitrification. It also illustrates that the denitrification process is not operating that well with average nitrate values of almost 10 mg/l. As ozonation and GAC are not expected to remove nitrate these values stay relatively constant throughout the process (Figures 4.2 and 4.3). The poor performance of the denitrification process was attributed to over oxygenation of the anoxic zone as the recycle from the membrane tank is highly aerated. At levels > 6 mg/l the nitrate concentrations would not meet the target water quality objectives. This is, however, not of immediate concern as on a full scale plant the inclusion of an anaerobic zone before the anoxic zone would provide better conditions for denitrification.

4.2.3 Soluble Reactive Phosphate and Total Phosphate

There is no SANS 241: 2011 drinking water standard for TP; therefore, the Darvill Wastewater Works discharge standard of 1.5 mg/l was used for operational comparison. From Figures 4.1 to 4.3, it can be seen that TP decreases through the process from MBR to GAC. Final average TP results are 1.49 mg/l in the GAC permeate. SRP, which is a more important determinand environmentally because of its impact on eutrophication, is much lower with an average SRP value of 0.9 mg/l (Figure 4.1).

4.2.4 Total Organic Carbon

The average TOC in the MBR permeate is 8.6 mg/l, and in the O_3/GAC permeate it is 5.1 mg/l. This represents a TOC percentage removal of 41%. This removal percentage is similar to that achieved at the New Goreangab Water Reclamation Plant, as reported by Menge et al. (2009), for the GAC unit (45%). Ozonation had far less impact on TOC (Figure 4.2), which may indicate that the organics are being broken down but not mineralized. No quantifiable difference in performance over time was identified in terms of TOC removal. Therefore the transformation of the GAC to a BAC once a biofilm has formed appears to have no impact on TOC removal (Figure 4.3). This has been confirmed by research by Najm et al. (2005), which showed that DOC and AOC removal three months after replacing a GAC-sand media was the same as was achieved after one year of operation.

4.2.5 UV_{254}

The absorption of ultraviolet light at wavelength 254 nm is used as an indicator of the presence of double bonds, aromaticity and molecules with high molecular weight (Theron-Beukes et al., 2008). The results for UV_{254} are excellent and are below the limit for final water at the NGRP of 0.065 UV_{254} /cm. (The UV_{254} results are not presented graphically).

4.2.6 Conductivity

The conductivity measured in mS/m is consistently below the SANS 241: 2011 drinking water standard of 170 mS/m. (The conductivity results are not presented graphically).

4.2.7 Microbial Content

Average coliphage and E.coli values were 5.6 CFU/100ml and 9.6 PFU/100 ml in the MBR permeate, compared to zero median values in both cases. These high values were unexpected and do not mirror the performance of the pilot plant in the past. The relatively poor performance in removing micro-organisms did, however, provide an opportunity for other downstream processes to be tested more thoroughly. Both ozonation and GAC proved extremely effective at removing coliphages and *E.coli* with zero CFU/100 ml at the 95th percentile. Coliform values in the MBR permeate (181 CFU/100 ml at the 95th percentile) were usually relatively high, but these were reduced markedly by ozonation to 26 CFU/100 ml at the 95th percentile. The count increased substantially in the GAC permeate to 477 CFU/100 ml at the 95th percentile, possibly due to breakthrough of bacteria from the GAC columns.

4.2.8 Turbidity

The median turbidity value of the MBR permeate is 0.27 NTU and this dropped to 0.21 NTU in the GAC permeate.

4.2.9 Summary

The ozone/GAC unit processes performed well in terms of reducing those determinands which these processes are expected to reduce, as can be seen by the fact that TOC is reduced on average by 42% and UV_{254} by 73%. Limited DOC removal (<14%) was observed in the ozonation stages showing that oxidation leads to the formation of transformation products rather than mineralization. This result is supported elsewhere in work undertaken by Reungoat et al. (2012), who showed similar limited reductions (<10%) in DOC, following ozonation. Menge et al. (2009) reported that DOC was reduced by only 5% following ozonation, at the Goreangab reclamation plant. Both studies reported that subsequent BAC filtration removed between 20 and 50% of the DOC. Results at Darvill show that 42% of TOC was removed after the ozone/GAC process step. The assumption is that the Darvill GAC has been operating as a BAC as it takes between 60–100 days for biofilm to form on the carbon.

Ozonation causes structural changes to natural organic matter (NOM) and particularly to the humic fractions. The changes include a strong and rapid decrease in colour and UV absorbance due to a loss of aromaticity and depolymerisation, a small reduction of TOC (e.g. 10% at 3 mgO_3 mgC-1), a slight decrease in the high apparent molecular weight fractions, and a slight increase in the smaller fractions. This was confirmed by Liquid Chromatography–Organic Carbon Detection (LC-OCD) analyses where the high apparent molecular weight fraction decreased from the MBR (409 g/mol) to 375 g/mol after ozonation.

In terms of the USEPA Disinfectants/Disinfection By-products Rule, D/DBPR (1st stage), the ozonation and GAC treatment steps worked effectively. The O_3/GAC treatment removes, on average, 40% of the TOC, which is as expected for feed water with an alkalinity of approximately 120 mEq/l and a TOC of approximately 8 mg/l (Table 2.13, Techneau, 2006). The feed water alkalinity from the MBR plant to the Ozone /GAC unit is on average 123 mg/l $CaCO_3$ and the TOC is 8.6 mg/l and therefore the 42% reduction in TOC is as expected.

Micro-biological contaminants such as *E.coli* and coliphages were generally entirely removed and both recorded zero median values. The median turbidity was also low at < 0.21 mg/l.

4.3 PERFORMANCE OF THE MBR-O_3/GAC-NF1, 2, 3, 4, 5 & 6 FLAT SHEET SYSTEM

4.3.1 Water Quality Results

In this section, results from the MBR-O_3/GAC-NF treatment train are presented. A UV radiation treatment step was not included. Six nanofiltration membranes (ESNA LF2, SR 90, Nano SW, NF 90, UTC 60A and NF 270) were compared in the MBR-O_3/GAC-NF process train. Comparison was made in terms of crucial contaminant removal with reference to drinking water standards and UV absorbance at 210, 254 and 280 nm. Preliminary results showed that contaminant removal efficiency depended on the membrane pore size with tighter NF 90 and ESNA1 LF 2 membranes having the highest rejection. The average TOC removal for all the investigated membranes was below 1 mg/l. However, removal of nitrates and total dissolved solids varied with pore size, with removal efficiency decreasing in the order: ESNA LF2, NF 90, Nano SW, SR 90, NF 270 and UTC 60A. UV_{210} absorbance removal was low in all the membrane permeates, indicating a pass though of smaller organics such as aldehydes, carboxylic acids and esters among others.

In general, product water from tighter NF membranes (NF 90 and ELSNA LF2) met drinking water standards, making MBR-O_3/GAC-NF a viable process choice for water reclamation. The permeate water quality results from the NF membrane tests are presented in the following sections. All filtration experiments were run at a cross-flow rate of 30 l/h, which translates to a cross-flow velocity of 0.08 m/s, and a constant temperature of the feed solution of 20 (±0.5) °C, controlled by a circulating heater/chiller. Pressure was also held constant at 10 bars except where it was the variable to be examined. The average flux rate for new membranes, at the above mentioned operating conditions, was 113 lmh. Permeability and flux rate decreased with time as fouling occurred, but was restored after cleaning as illustrated in Figure 4.4, and Tables 4.2–4.5.

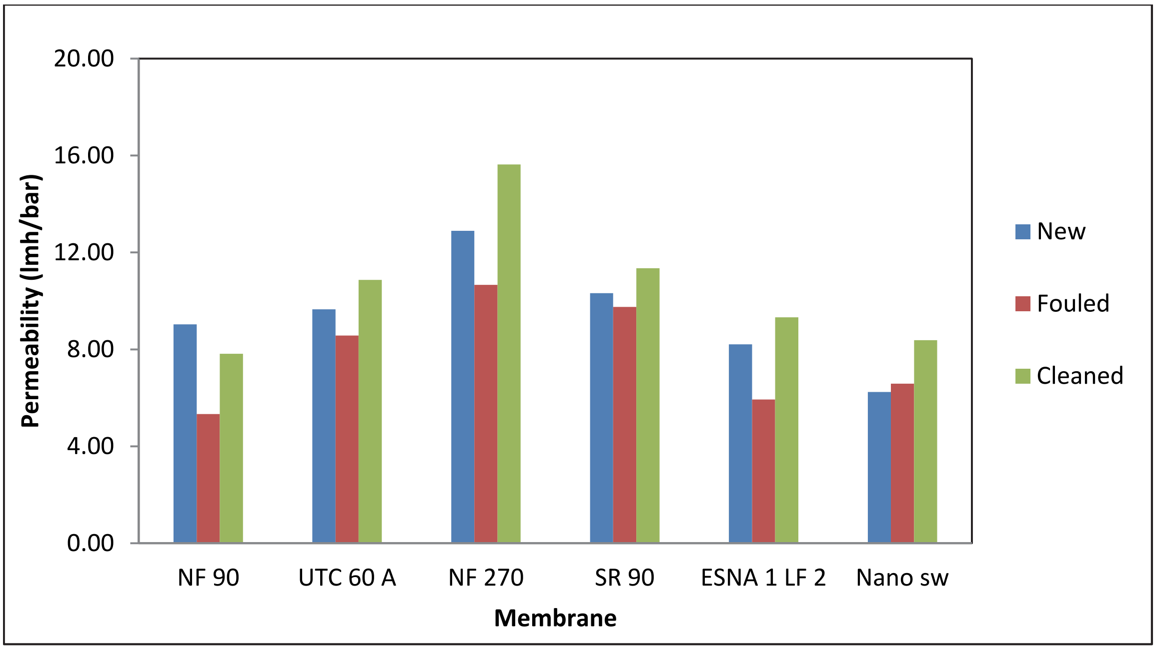


Figure 4.4: NF Flat Sheet Permeability (lmh/bar)

Table 4.2: NF Flat Sheet Permeability

	Permeability (lmh/bar)		
Membrane	**New**	**Fouled**	**Cleaned**
NF 90	9.03	5.33	7.82
UTC 60A	9.65	8.57	10.87
NF 270	12.89	10.66	15.63
SR 90	10.32	9.75	11.35
ESNA 1 LF 2	8.21	5.93	9.33
Nano SW	6.24	6.58	8.38

Table 4.3: NF Flat Sheet Membrane Flux Rate Change

	Virgin membrane		Fouled membrane		Cleaned membrane	
Pressure (bars)	**Vol (ml)**	**Flux(lmh)**	**Vol (ml)**	**Flux (lmh)**	**Vol (ml)**	**Flux (lmh)**
NF 90						
5	3.9	46.8	2.5	30	3.5	42
10	7.6	91.2	4.1	49.2	6.5	78
15	11.2	134.4	6.8	81.6	9.7	116.4
UTC 60A						
5	2.15	51.6	1.8	43.2	2.1	50.4
10	4	96	3.5	84	4.6	110.4
15	6	144	5.4	129.6	6.8	163.2
NF 270						
5	2.8	67.2	2.5	60	3.5	84
10	5.4	129.6	4.1	98.4	6.5	156
15	8	192	6.8	163.2	9.7	232.8
SR 90						
5	4	48	4.1	49.2	5	60
10	8.9	106.8	7.8	93.6	9.6	115.2
15	12.8	153.6	12.4	148.8	14	168
ESNA						
5	3.8	45.6	3.1	37.2	4.8	57.6
10	6.9	82.8	5.1	61.2	8	96
15	10.1	121.2	7.1	85.2	11.2	134.4
Nano SW						
5	2.8	33.6	3	36	3.1	37.2
10	5.1	61.2	5.7	68.4	7	84
15	7.8	93.6	8	96	10.6	127.2

Table 4.4: NF Summarised Permeate Water Quality Results

MBR-GAC-NF1, 2 & 3		NF SR90 (NF1) Dow Filmtec				NF ESNA1-LF2 (NF2) Hydranautics				NF NANO SW (NF3) Hydranautics			
	Units	Mean	Median	STD	95%	Mean	Median	STD	95%	Mean	Median	STD	95%
Alkalinity	mE/l	27.75	26.90	15.51	58.85	12.41	10.00	4.36	20.42	20.90	19.20	11.42	41.70
Coliforms	CFU/100ml	129.91	28.00	264.37	699.30	181.39	12.00	865.34	178.50	84.41	15.00	289.77	252.60
Coliphages	PFU/100ml	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EC	mS/m	25.77	24.20	5.79	36.37	5.24	3.73	3.66	13.16	20.26	19.15	6.32	33.32
E. coli	CFU/100ml	0.00	0.00	0.00	0.00	0.23	3.73	1.10	0.55	0.07	0.00	0.37	0.00
NH_3	mg/l	1.05	0.50	1.47	5.07	0.66	0.50	0.42	1.56	0.98	0.50	1.20	3.48
NO_3	mg/l	8.55	7.49	4.91	17.62	1.71	1.12	1.39	4.35	8.51	7.76	5.01	16.93
TKN	mg/l	3.11	3.00	0.51	3.71	3.00	3.00	0.00	3.00	3.00	3.00	0.00	3.00
SRP	µg P/l	0.10	0.10	0.00	0.10	0.10	0.10	0.00	0.10	0.10	0.10	0.00	0.10
TP	µg P/l	0.50	0.50	0.00	0.50	0.88	0.50	2.12	0.50	0.50	0.50	0.00	0.50
TOC	mg/l	0.75	0.70	0.16	1.08	0.72	0.70	0.10	0.84	0.80	0.70	0.63	0.81
Turbidity	mg/l	0.22	0.18	0.16	0.38	0.22	0.19	0.10	0.39	0.25	0.25	0.12	0.45
pH	mg/l	7.70	7.70	0.38	8.32	7.40	7.53	1.06	8.05	7.44	7.42	0.45	8.13
TDS	mg/l	89.00	89.00	0.00	89.00								

Table 4.5: NF Summarised Permeate Water Quality Results

MBR-GAC-NF 4, 5& 6		NF 90 (NF4) Dow Filmtec				NF 270 (NF5) Dow Filmtec				NF UTC60A (NF6) Toray			
	Units	**Mean**	**Median**	**STD**	**95%**	**Mean**	**Median**	**STD**	**95%**	**Mean**	**Median**	**STD**	**95%**
Alkalinity	mE/l	10.00	10.00	0.00	10.00	38.45	38.45	4.74	41.47	18.68	18.80	5.00	24.10
Coliforms	CFU/100ml	9.56	5.00	14.91	33.60	24.00	28.00	16.54	40.80	33.67	34.00	27.76	63.00
Coliphages	PFU/100ml	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EC	mS/m	4.84	3.70	4.70	9.54	21.22	24.40	9.45	29.61	20.32	21.20	5.04	25.11
E. coli	CFU/100ml	0.00	0.00	0.00	0.00	0.40	0.00	0.89	1.60	0.00	0.00	0.00	0.00
NH3	mg/l	0.50	0.50	0.00	0.50	0.50	0.50	0.00	0.50	0.50	0.50	0.00	0.50
NO3	mg/l	2.58	1.69	2.55	6.06	9.72	8.41	2.60	12.96	9.37	8.89	2.72	12.96
TKN	mg/l	3.00	3.00	0.00	3.00	3.00	3.00	0.00	3.00	3.00	3.00		3.00
SRP	µg P/l	0.10	0.10	0.00	0.10	0.10	0.10	0.00	0.10	0.10	0.10	0.00	0.10
TP	µg P/l	0.50	0.50	0.00	0.50	0.50	0.50	0.00	0.50	0.50	0.50	0.00	0.50
TOC	mg/l	0.73	0.70	0.06	0.88	0.72	0.70	0.04	0.79	0.72	0.70	0.07	0.82
Turbidity	mg/l	0.26	0.22	0.15	0.48	0.24	0.21	0.18	0.51	0.23	0.18	0.11	0.43
pH	mg/l	7.22	7.19	0.36	7.81	7.56	7.62	0.27	7.86	7.50	7.45	0.18	7.78

These tests were conducted to compare the fouling propensity and ease of cleaning of the flat sheets at bench scale, hence the operating conditions do not relate to the spiral operating conditions in full scale applications. This is why the flux rate is far higher than the standard operating flux of about 20 lmh in full scale plants. The cleaning chemical used was a 0.1 % NaOH solution, and cleaning was done at 1 bar for 15 minutes using a peristaltic pump

4.3.2 Solute Rejection

Solute rejection remains one of the priority reasons for the employment of membrane filtration steps in reclamation process trains. In this study, the ability of the membranes to reject solutes was evaluated in relation to TDS, conductivity, alkalinity and nitrates rejection. All the solute rejection experiments, except for TDS, were conducted over a six month period and the graphed results are the averages over the period. The NF membranes under consideration were subjected to a feed with total dissolved solids concentration of 494 mg/l at the 95th percentile. Figure 4.5 shows the variation of the permeate TDS in the time domain. NF 90 and ESNA1 LF2 had the highest rejection of the dissolved solutes which may be attributed to their smaller pore sizes (see Table 3.1).

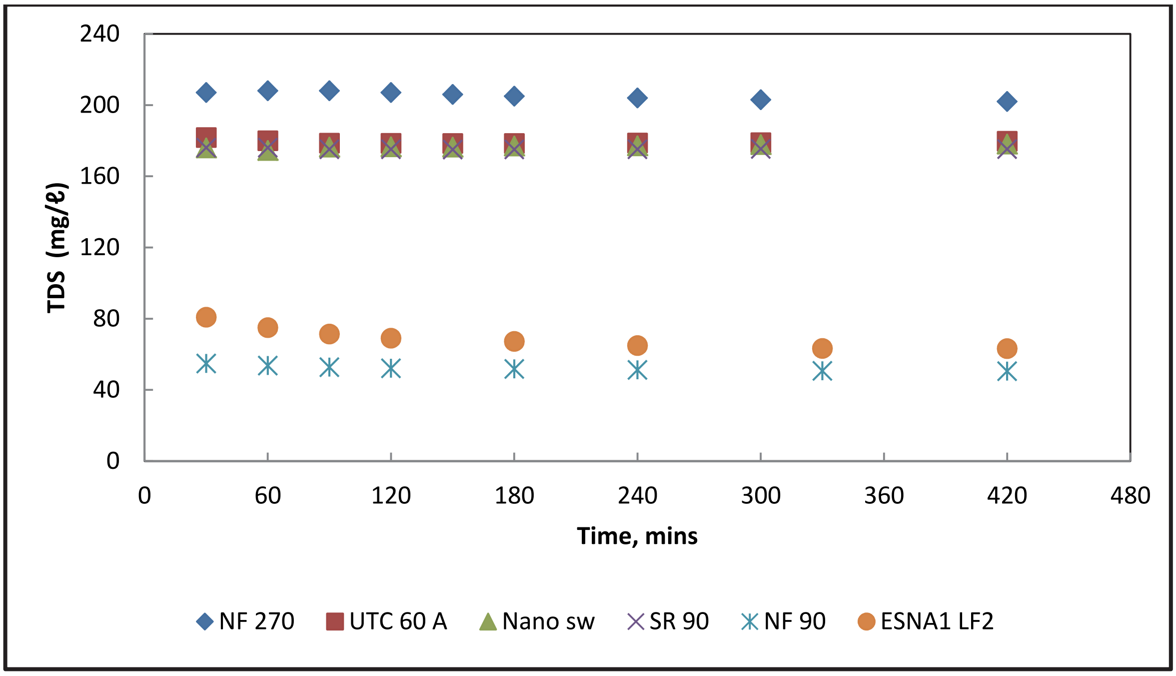


Figure 4.5: TDS v Time Plots for the NF Membranes

Though the permeate TDS remained fairly constant with time for most of the membranes, there was a gradual decrease in the ESNA1 LF2 permeate for the first three hours before leveling off. This could be due to the combined effect of this membrane's small pore size and high surface roughness (see Table 3.1) which sets in fouling and hence pore restriction at the present operating conditions, which gradually enhances its TDS rejection.

Figure 4.6 presents the average nitrate rejection by the membranes. It can be seen that separation efficiency was highest in NF 90 (78%) and ESNA1 LF2 (84%). However, there was almost zero rejection by Nano-SW and UTC 60 A.

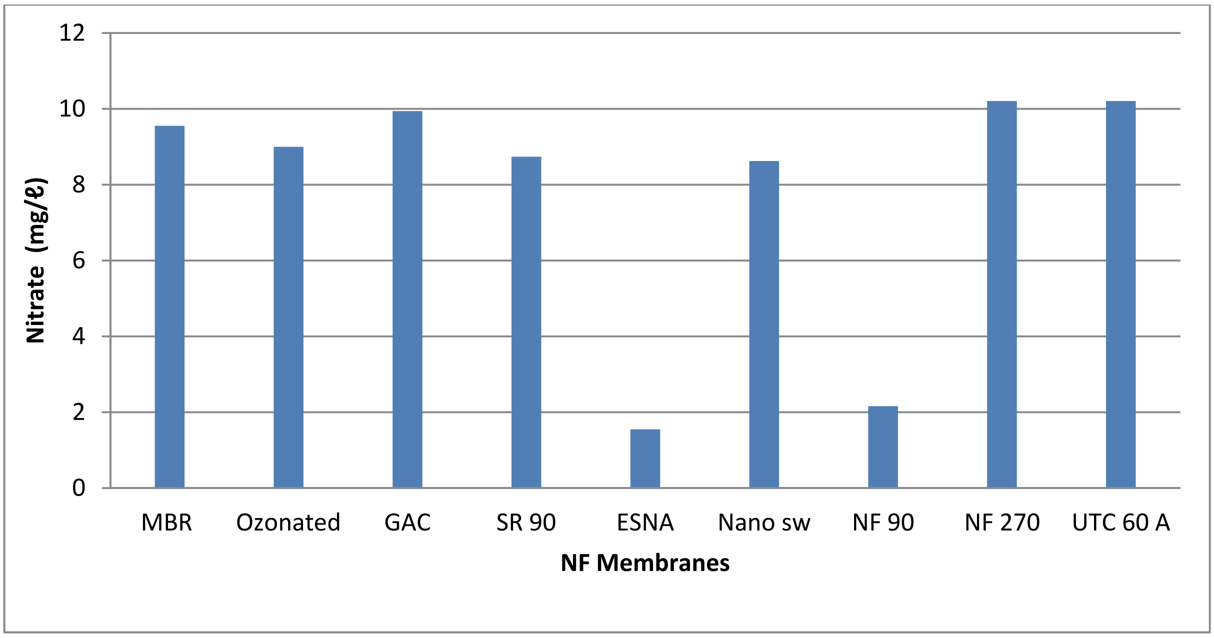


Figure 4.6: Nitrates Rejection by the NF Membranes

Likewise, highest conductivity rejections were noted in the permeates of the NF 90 (95%) and ESNA1 LF2 (94%) membranes. The conductivity rejection plots are presented in Figure 4.7. Similarly, the six month averaged results for permeate alkalinity indicate that these membranes are the best performers, as shown in Figure 4.8.

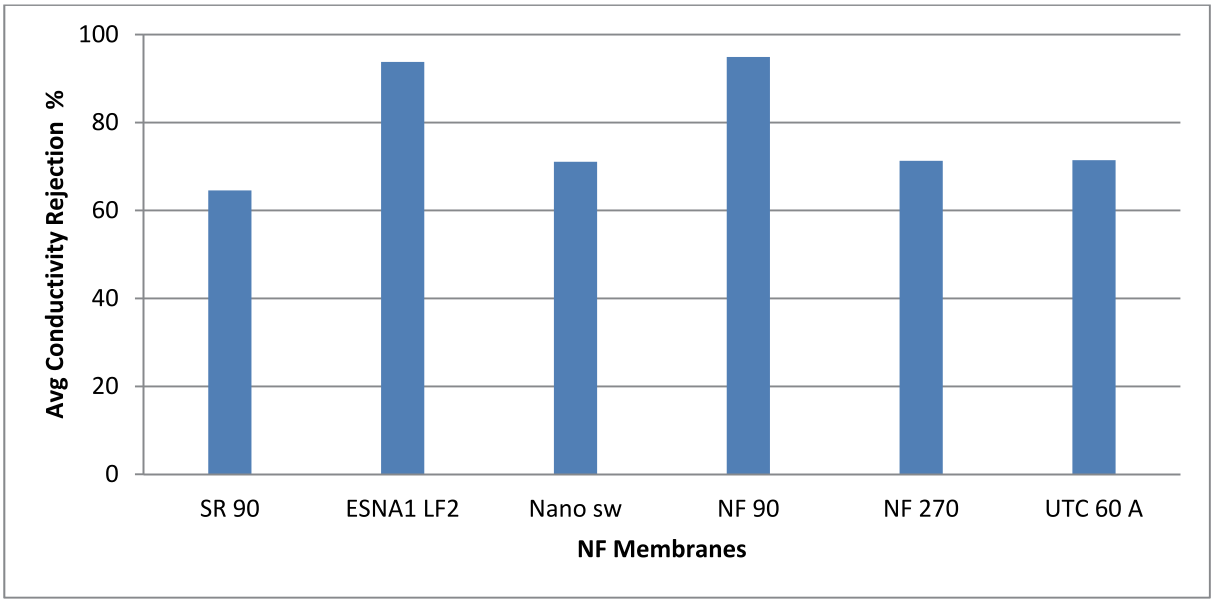


Figure 4.7: Average Conductivity Rejection by the NF Membranes

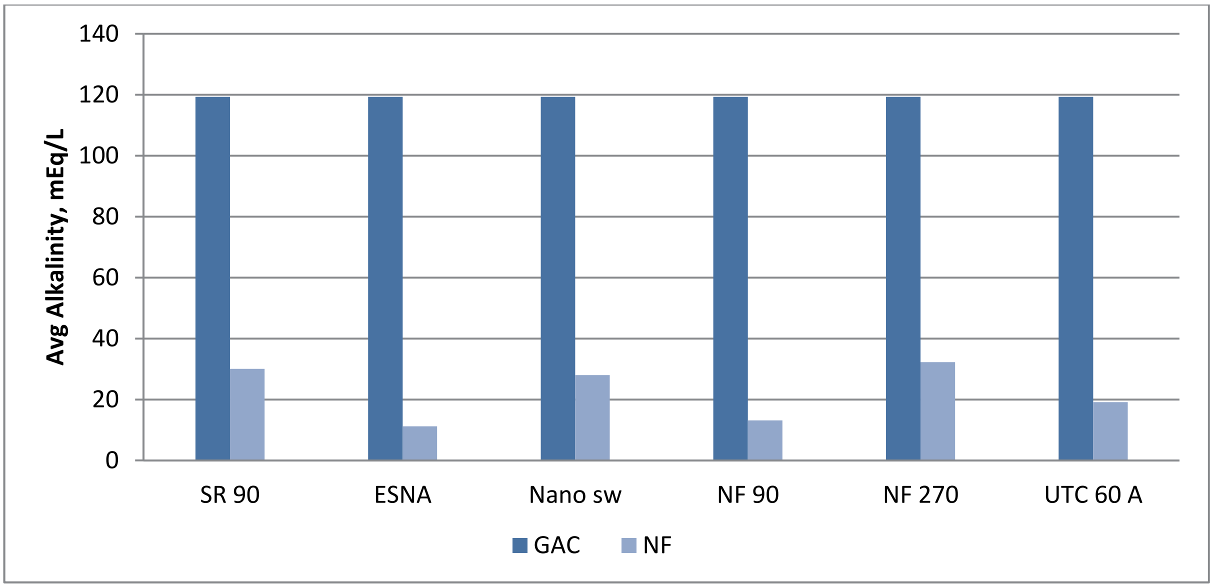


Figure 4.8: Alkalinity Levels in Product Water

4.3.3 Organic Matter Rejection

Removal of NOM is important since NOM acts as a precursor to disinfection by-products. The most popular predictor of NOM rejection by membranes has been the nominal MWCO. Often, different relative molecular mass rejections have been observed for different membranes with comparable nominal MWCOs and for the same membranes when applied to different solutes, including NOM source waters. As a surrogate measure, UV absorbance reductions were evaluated at 210, 254 and 280 nm and the results are presented as a graph in Figure 4.9. In general, for all six membranes, higher UV absorbance removal was witnessed at 254 nm and 280 nm, indicating higher rejections of characteristic aromatic and protein organic molecules respectively.

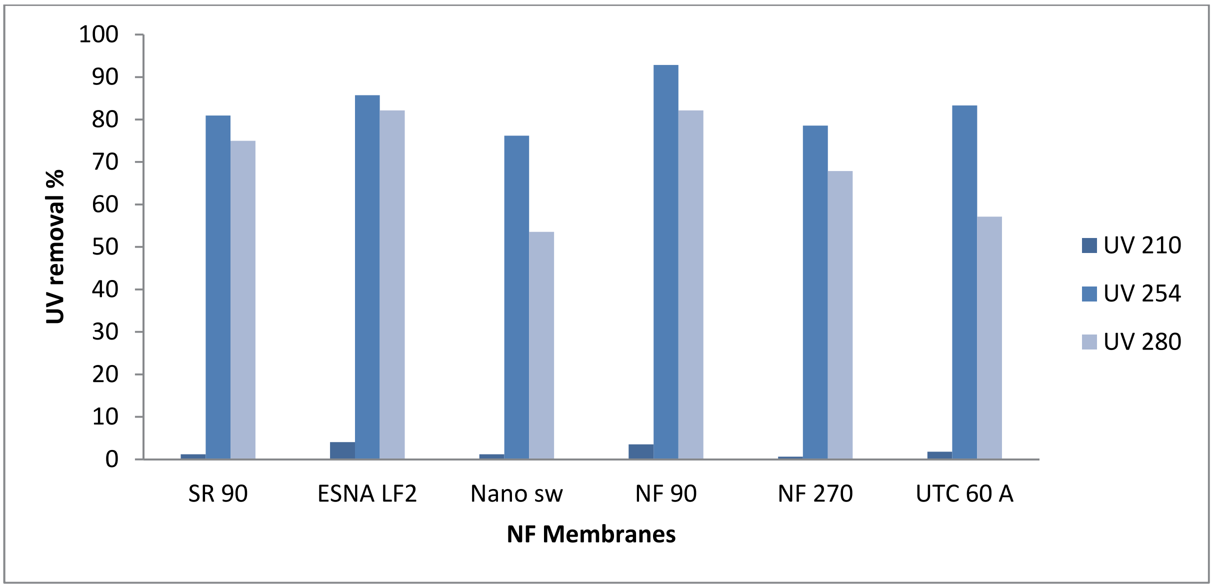


Figure 4.9: UV Absorbance

In terms of overall organics rejection, there was insignificant difference between the membranes, as shown in Figure 4.10. From these results, it can be said that organic carbon rejection is not only attributed to a sieving mechanism but also to other mechanisms such as a charge effect which can intervene in its rejection.

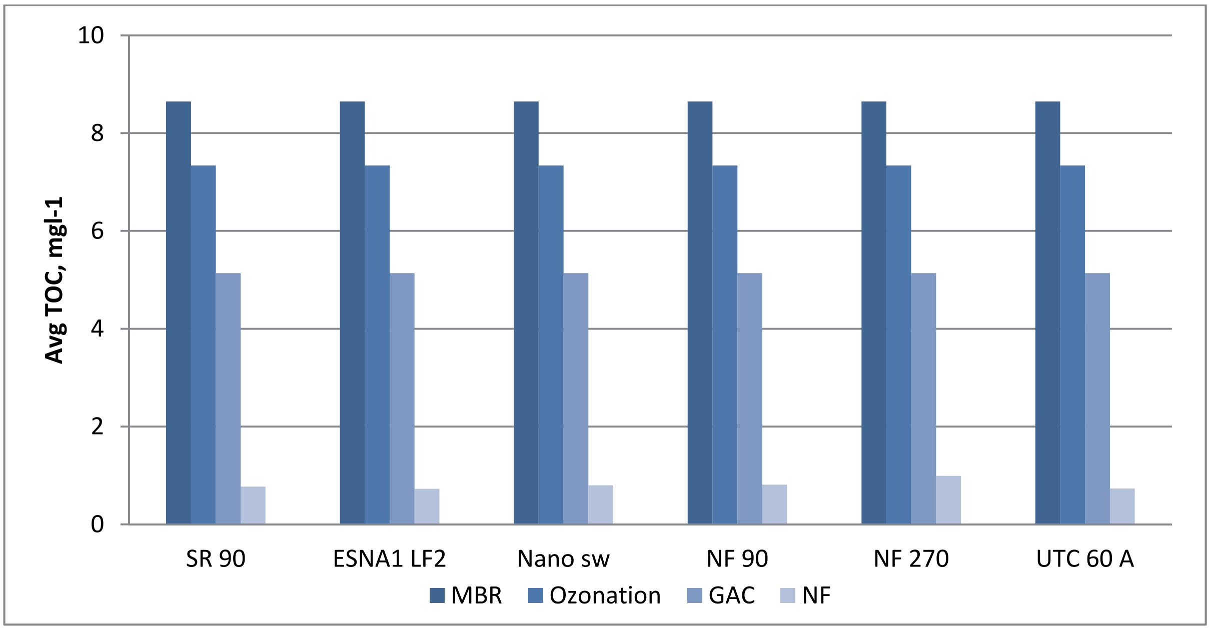


Figure 4.10: Average TOC Levels

4.3.4 Microbial Content

One of the most critical wastewater contaminants targeted in any reclamation scheme is the microbial content. Three groups of microorganisms, *E. coli*, coliphages and coliforms, were analysed in the product streams of the reclamation units. From the preliminary results, the E. coli and coliphage counts were consistently zero after the ozonation and GAC processes. However, after the NF process, the coliform and *E. coli* counts followed a different trend. There was a noticeable increase in coliforms after membrane filtration. This was attributed to permeate recontamination after the membranes probably due to the porous stainless steel membrane support. There were also one or two counts where *E. coli* was recorded, though at very low levels (2 CFU/100 ml). These results are suspected as being a result of contamination during sampling.

4.3.5 Turbidity

Following MBR, turbidity is reduced to < 1 NTU. This value is halved to < 0.5 NTU at the 95th percentile by all the NF membranes and thus meets the target water quality objective.

4.3.6 Optimal Operating Pressure for ESNA-LF2 and NF 90

A major limitation of membrane application processes is membrane fouling. With cross-flow velocity held constant at 0.08 ms^{-1}, operating pressures for NF 90 and ESNA1 LF2 were sought at which flux decline with time does not occur. At these optimal pressures, dynamic equilibrium is attained where the rate of solute/foulant deposition on the membrane surface is equivalent to back diffusion/transport. From Figure 4.11, it is evident that the optimal pressure for ESNA1 LF2 is about 4 bars. At this pressure, the flux remained fairly constant with time. NF 90 had a higher optimal pressure of about 7 bars (Figure 4.12). This high pressure is attributed to its lower surface roughness as compared to ESNA1 LF2, hence less fouling propensity.

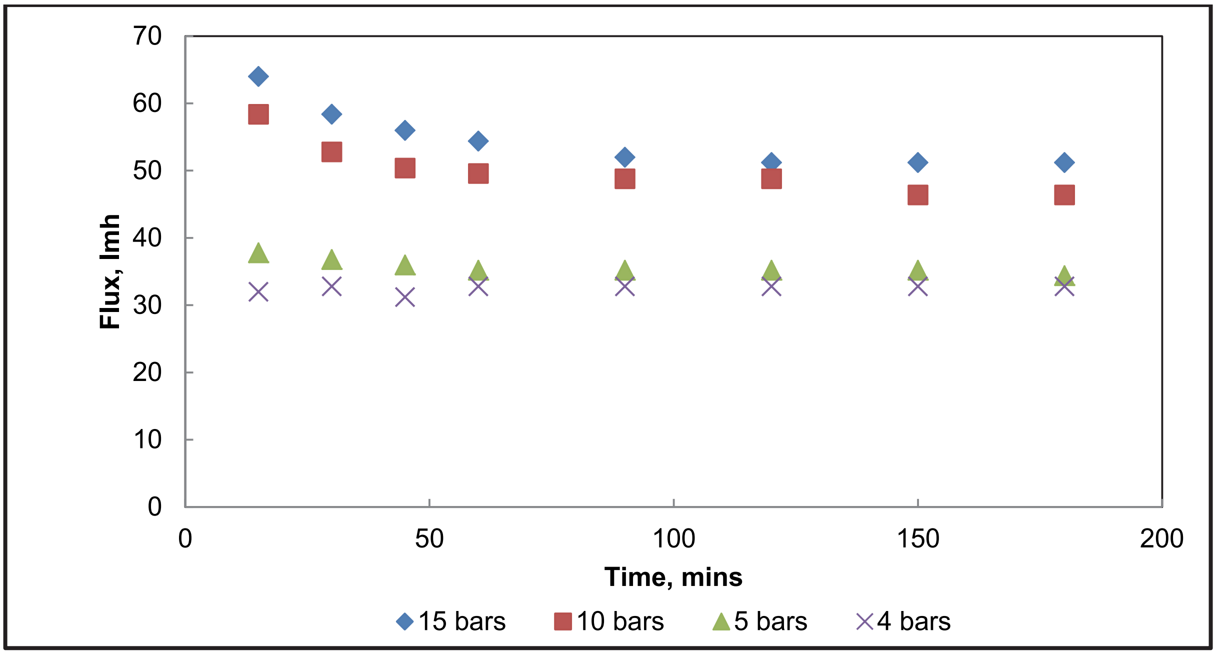


Figure 4.11: Effect of Operating Pressure on ESNA1 LF2 Permeate Flux

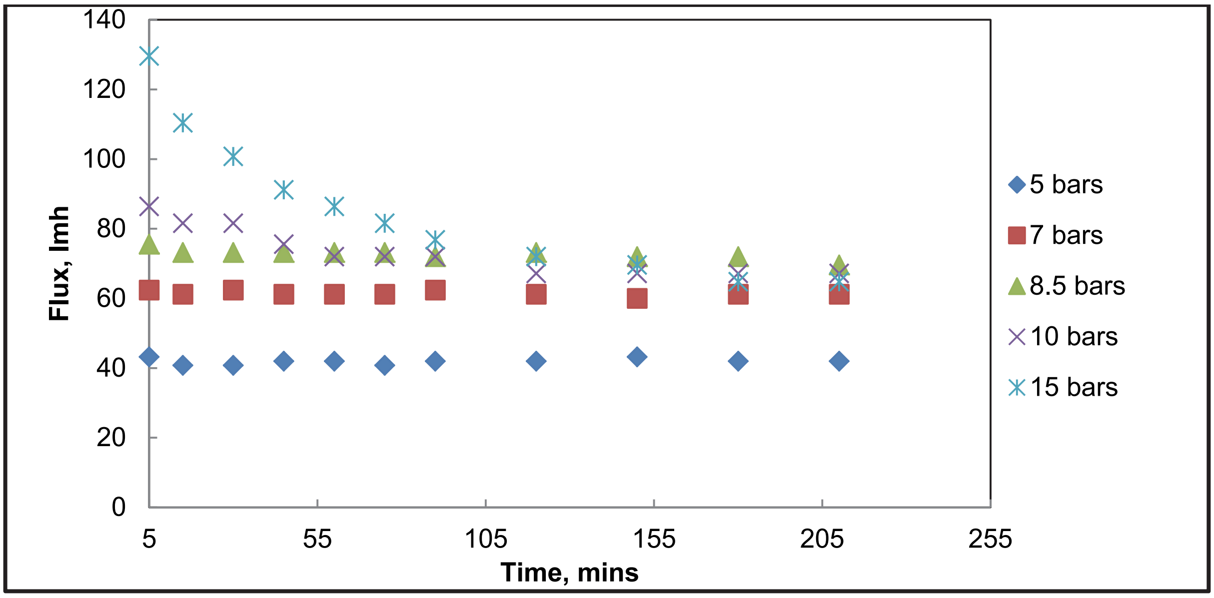


Figure 4.12: Effect of Operating Pressure on NF 90 Permeate Flux

4.3.7 Summary

The effectiveness of nanofiltration in the removal of undesirable components from wastewater in the MBR, ozonation, GAC and NF process train has been investigated. Among the considered NF membranes, NF 90 from Dow Filmtec and ESNA1 LF2 from Hydranautics displayed the highest rejection efficiencies in rejection of inorganic solutes. This was attributed to their smaller pore sizes. However, the membranes performed very similarly in terms of organics rejection levels and in relation to the other determinands reported on. From these preliminary investigations, NF 90 and ESNA1 LF2 were found to be the best performers and hence are proposed for further testing (continuous flow) and use at pilot-scale. A benchmark for the performance of the NF-90 membrane as a spiral wound membrane tested under continuous feed flow conditions was reported on in (Drewes et al., 2005). A two stage membrane laboratory-scale unit employed two single element (4040 spiral wound) vessels arranged in a two stage array. The NF-90 membrane achieved similar removal to RO membranes. While providing similar water quality, the NF-90 membrane can be operated at significantly lower feed pressures. The results suggest that NF membranes are viable for water reuse projects where a high permeate quality is required (Drewes et al., 2005).

4.4 PERFORMANCE OF THE MBR-O_3/GAC-NF SPIRAL WOUND TREATMENT SYSTEM

4.4.1 Water Quality Results

The flat sheet NF membranes were previously compared (Section 4.3) in terms of their product water quality. The NF90 and ESNA-LF2 membranes were the best performing and therefore these membranes were targeted for continuous flow testing using spiral wound membranes. Unfortunately, no spiral wound membranes for these two makes were available from the manufacturers at the time. The only spiral wound NF membrane that could be obtained was the SR90 Dow Filmtec. The SR90 NF membrane performed relatively well in the earlier trials so there was no reason why this membrane could not be used. The spiral wound trials are undertaken to replicate full scale operational conditions to a greater extent. The flow rate and operating pressure is far higher and the flow rate is continuous. Membrane performance over time can be tested, specifically in relation to fouling. The permeate water quality from the MBR-O_3/GAC-NF spiral wound treatment train is presented in Figures 4.13 and 4.14.

4.4.2 Solute Rejection

The average concentration of NH_3, SRP, TP and TOC in the permeate is less than 1 mg/l. The exception is NO_3 which is not removed by NF. The nitrate level exceeds the targeted water quality objective and the SANS 241 (2011) drinking water limit of 6 mg/l. The high nitrate concentrations are a symptom of the poor denitrification process in the MBR pilot plant process. In Figure 4.14, a sharp reduction in alkalinity of the GAC effluent from 123 mg/l to average concentrations of 57 mg/l is noticeable due to the ability of NF to remove divalent ions. Salinity levels are, however, relatively unchanged with the average TDS concentration in the NF permeate being 206 mg/l. The reduction in alkalinity may make the product water slightly aggressive, but this will be affected by other factors such as hardness, pH, carbon dioxide, oxidizing agents (e.g. DO) and TDS.

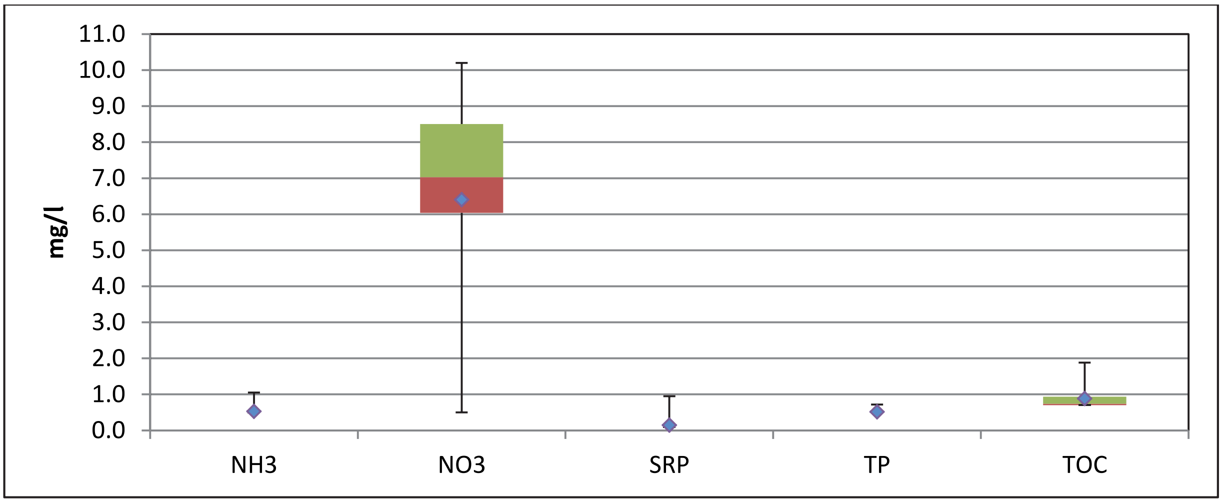


Figure 4.13: MBR-O_3/GAC-NF (SR 90) Permeate Water Quality

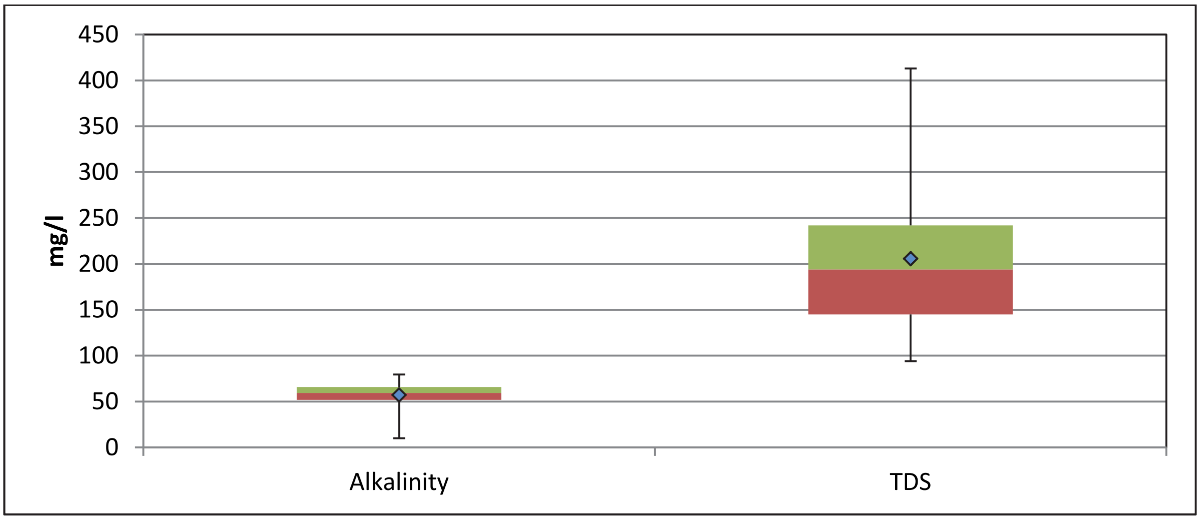


Figure 4.14: MBR-O_3/GAC-NF (Spiral Wound) Permeate Water Quality

4.4.3 Microbial Content

Coliforms, coliphages and *E.coli* recorded zero after the NF membrane. This proves that the high levels (699 CFU/100 mg/L) recorded at the 95th percentile in the NF flat sheet membranes were due to contamination.

4.4.4 Turbidity

Average turbidity was 0.28 NTU and 0.51 NTU at the 95th percentile.

4.4.5 Summary

The MBR-O_3/GAC-NF process produces water of potable quality that meets SANS 241 (2011) drinking water standards, with the exception of nitrate concentration. It is, however, assumed that with a better performing biological system, the nitrate concentration can be reduced sufficiently to meet requirements. This assumption is based on the fact that a full scale plant with a correctly designed anaerobic zone will provide the necessary conditions for denitrification.

These results should, however, be qualified as follows:

- The duration of the NF/RO spiral wound membrane testing was short (1 week) compared to the typical operating life of a membrane system and therefore will only provide an indication of performance. Such short-term experimental work cannot be extrapolated over the life of a full scale industrial facility.
- The experimental results also reflect membrane performance at the upstream end of a membrane pressure vessel. The performance may be different at the downstream end of the membrane vessel if it is affected by the concentration gradient.
- The NF/RO spiral wound membranes were being operated at 30% recovery, which also does not reflect membrane operation on a full scale plant. In order to test the membranes at much higher recoveries (70–85%) experiments were run in which the concentrate was recirculated. In this way the experiments simulated the concentrations that would be experienced by six to eight membranes in series in a membrane vessel. These recovery experiments are, unfortunately, not yet available.

4.5 PERFORMANCE OF THE MBR-RO FLAT SHEET SYSTEM

4.5.1 Water Quality Results

The MBR-RO-UV process train is intended to mimic the NEWater process train (MF/UF-RO-UV) to a large extent. The UV radiation unit was not installed for this particular set of results, because the flow rate obtained from the flat sheet membrane cell is not enough to be used by the high flow rate UV radiation unit. The MBR-RO final water quality results (Tables 4.6 and 4.7) are similar to those that were achieved with the full MBR-O3/GAC-NF (flat sheet) process train reported on in Section 4.3. The degree of efficacy of this treatment train will become more apparent later in the study when the results from the EDC sampling and analyses are available. The product water results are presented graphically in Figures 4.15–4.19.

Table 4.6: Summary of RO Permeate Water Quality Results

MBR-RO		**MBR Permeate**				**UTC70B (RO1) Toray**				**UTC70UB (RO2) Toray**			
	Units	**Mean**	**Median**	**STD**	**95%**	**Mean**	**Median**	**STD**	**95%**	**Mean**	**Median**	**STD**	**95%**
Alkalinity	mE/l	126.38	125.00	37.42	195.00	10.56	10.00	2.40	11.17	17.67	10.00	32.70	21.10
Coliforms	CFU/100ml	37.53	10.00	52.32	148.40	46.82	10.00	15.69	209.10	32.35	13.50	43.30	128.50
Coliphages	PFU/100ml	2.58	0.00	4.72	11.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EC	mS/m	68.35	66.00	9.29	88.13	1.36	0.96	0.96	3.37	1.63	1.08	2.86	3.08
E. coli	CFU/100ml	2.11	0.00	4.45	13.25	0.00	0.00	0.00	0.00	1.00	0.00	3.44	6.25
NH3	mg/l	1.37	0.50	3.26	7.05	0.50	0.50	0.00	0.50	0.50	0.50	0.00	0.50
NO3	mg/l	8.89	8.26	5.35	19.22	0.54	0.50	0.13	0.83	0.53	0.50	0.06	0.66
TKN	mg/l	3.71	3.00	2.95	7.48	3.11	3.00	0.64	3.49	3.01	3.00	0.05	3.00
SRP	µg P/l	1.68	0.20	2.13	6.08	0.10	0.10	0.00	0.10	0.10	0.10	0.00	0.10
TP	µg P/l	2.03	0.50	2.34	6.03	0.50	0.50	0.00	0.50	0.50	0.50	0.00	0.50
TOC	mg/l	8.40	8.44	1.84	10.74	0.98	0.70	1.64	1.00	0.72	0.70	0.07	0.78
Turbidity	mg/l	0.31	0.29	0.17	0.63	0.23	0.17	0.26	0.44	0.20	0.18	0.10	0.38
pH	mg/l	7.47	7.47	0.22	7.80	7.31	7.34	0.54	7.92	7.02	7.01	0.60	7.63
TDS	mE/l	143.80	134.00	39.74	201.65								

Table 4.7: Summary of RO Permeate Water Quality Results

MBR-RO		MBR Permeate				LFC3 (RO3) Hydranautics				XLE (RO4) Dow Filmtec			
	Units	**Mean**	**Median**	**STD**	**95%**	**Mean**	**Median**	**STD**	**95%**	**Mean**	**Median**	**STD**	**95%**
Alkalinity	mE/l	126.38	125.00	37.42	195.00	10.00	10.00	0.00	10.00	10.00	10.00	0.00	10.00
Coliforms	CFU/100ml	37.53	10.00	52.32	148.40	44.67	24.50	40.70	103.50	2.60	1.00	4.22	8.40
Coliphages	PFU/100ml	2.58	0.00	4.72	11.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
EC	mS/m	68.35	66.00	9.29	88.13	1.09	0.95	0.47	1.92	0.98	0.83	0.45	1.73
E. coli	CFU/100ml	2.11	0.00	4.45	13.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
NH_3	mg/l	1.37	0.50	3.26	7.05	0.50	0.50	0.00	0.50	0.50	0.50	0.00	0.50
NO_3	mg/l	8.89	8.26	5.35	19.22	0.54	10.00	0.00	10.00	0.99	0.55	1.41	3.03
TKN	mg/l	3.71	3.00	2.95	7.48	3.00	3.00	0.00	3.00	3.00	3.00	0.00	3.00
SRP	µg P/l	1.68	0.20	2.13	6.08	0.10	0.10	0.00	0.10	0.10	0.10	0.00	0.10
TP	µg P/l	2.03	0.50	2.34	6.03	0.50	0.50	0.00	0.50	1.06	0.50	1.59	3.43
TOC	mg/l	8.40	8.44	1.84	10.74	0.72	0.70	0.06	0.83	0.70	0.70	0.00	0.70
Turbidity	mg/l	0.31	0.29	0.17	0.63	0.26	0.24	0.14	0.50	0.18	0.17	0.08	0.31
pH	mg/l	7.47	7.47	0.22	7.80	6.86	6.70	0.63	8.04	6.34	6.27	0.22	6.65
TDS	mE/l	143.80	134.00	39.74	201.65								

4.5.2 Solute Rejection

Figure 4.15 presents the reduction in alkalinity. Alkalinity is reduced to below the detection limit of 10 mE/l $CaCO_3$, by all but one of the RO membranes. Ammonia and nitrate (Figure 4.16) are reduced to below 1 mg/l by the RO membranes. SRP and TP (Figure 4.17) are reduced to below 0.5 mg/l with the exception of the XLE (Dow Filmtec) membrane. Generally, the RO membranes are shown to be capable of removing inorganic nutrients to well below the target water quality objectives. The performance of the RO membranes in terms of salt rejection is illustrated in Figure 4.18, with all the membranes achieving greater than 97% rejection.

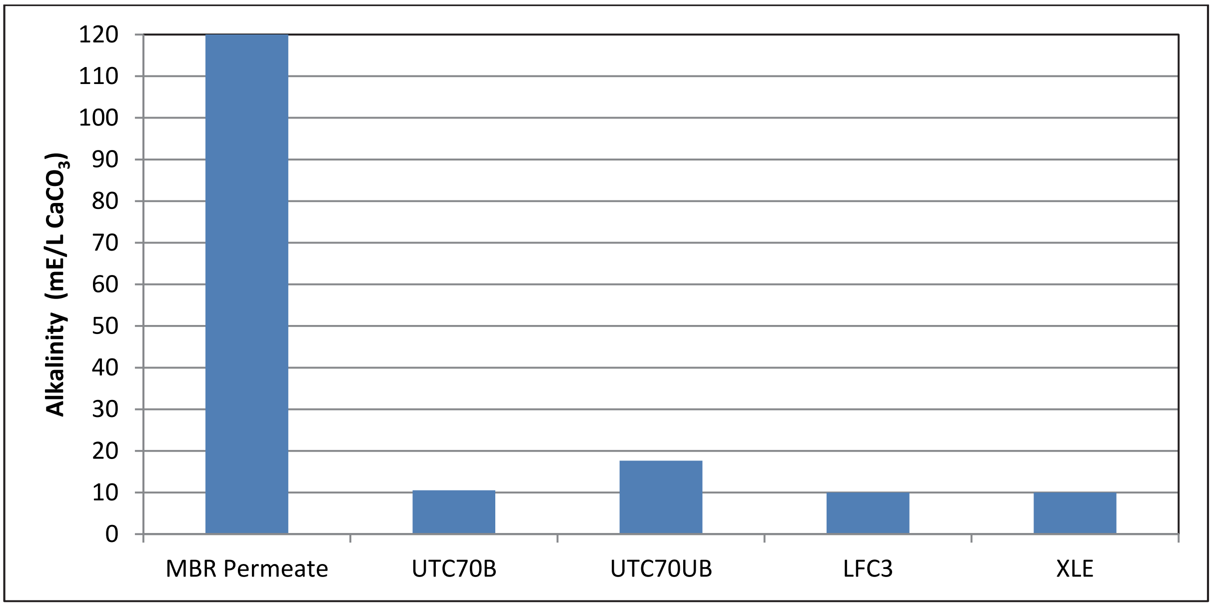


Figure 4.15: Average Alkalinity Levels in Product Water

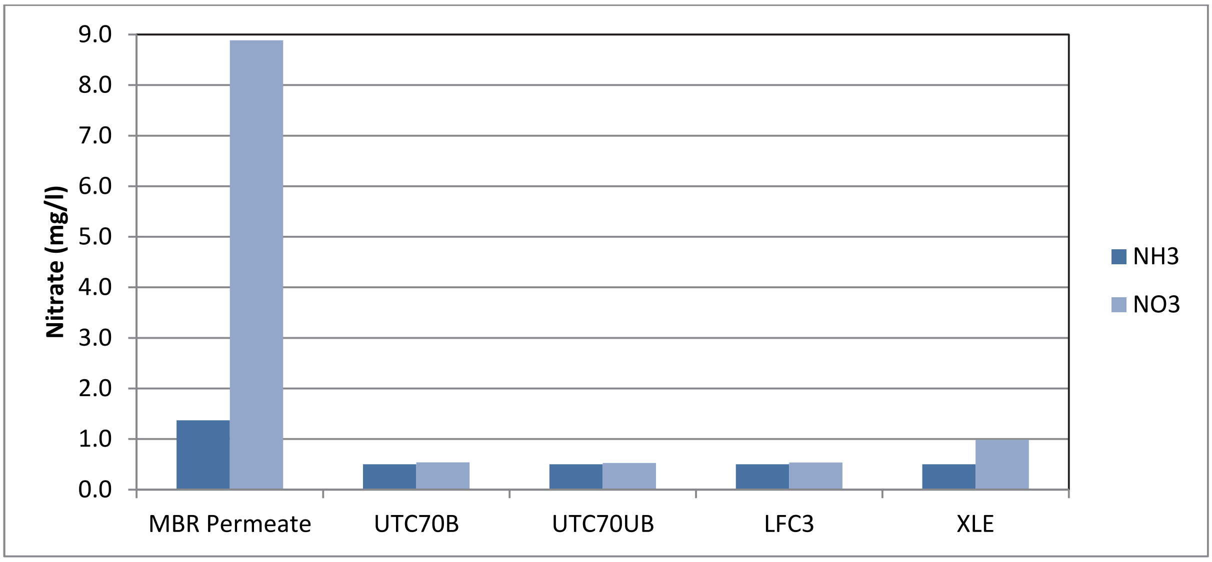


Figure 4.16: Average Nitrate Levels in Product Water

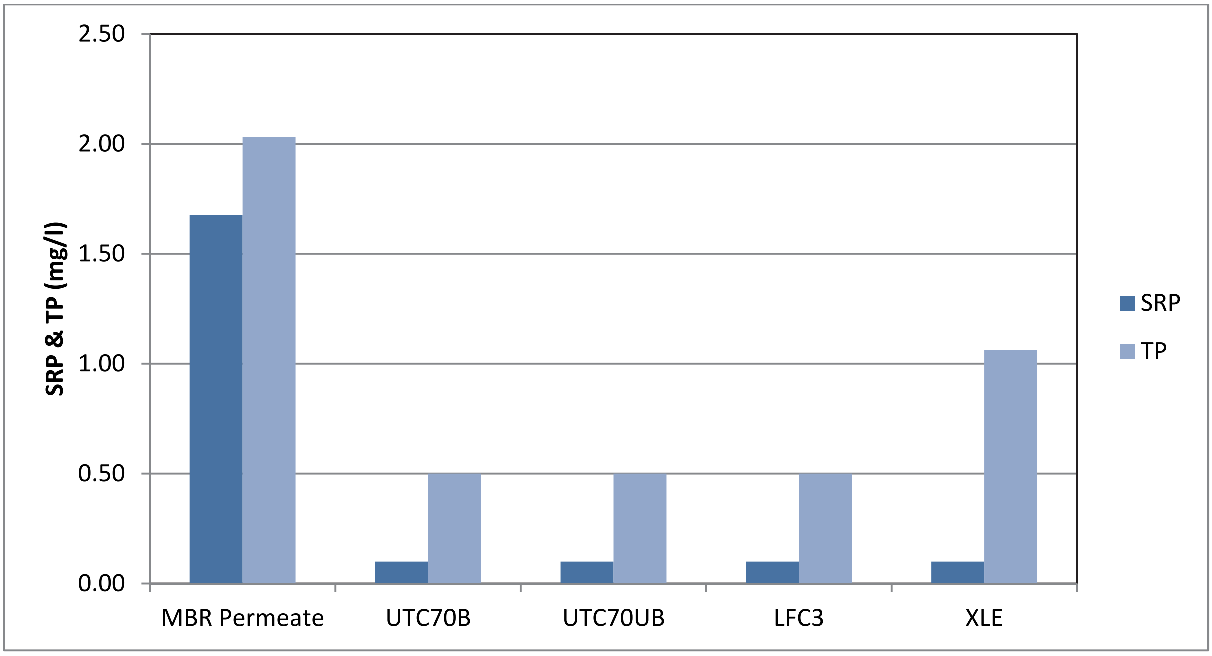


Figure 4.17: Average SRP and TP Levels in Product Water

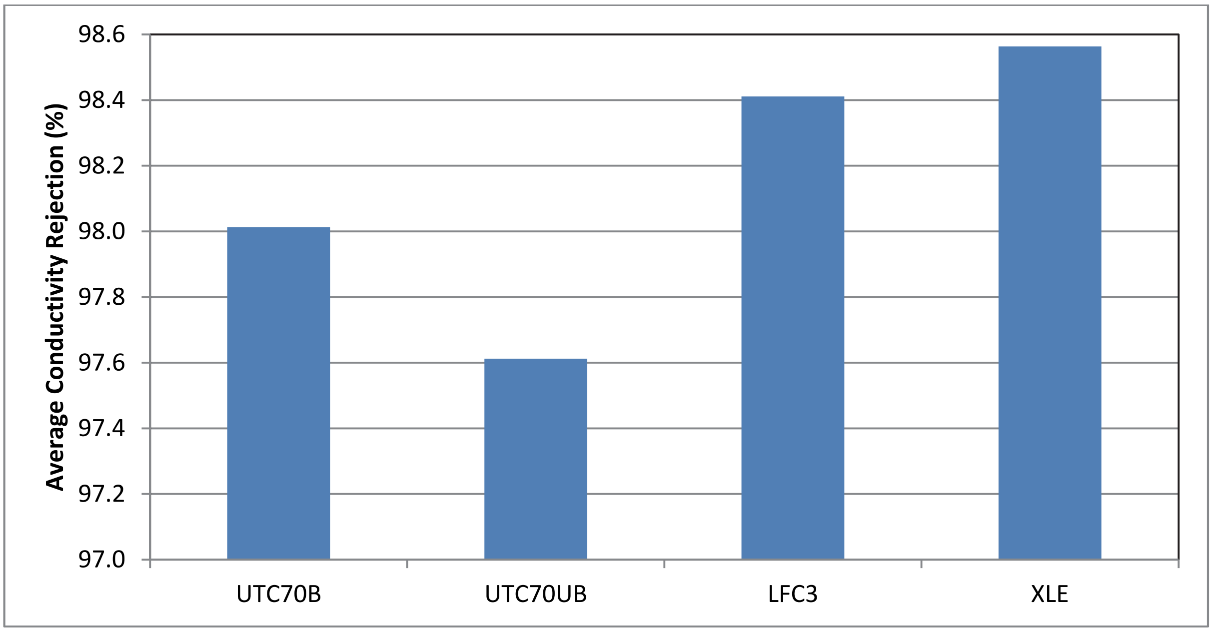


Figure 4.18: Average Conductivity Rejection by the RO Membranes

4.5.3 Organic Matter Rejection

The final water TOC (Figure 4.19) is lower than the detection limit of 0.7 mg/l as was the case in the MBR-O_3/GAC-NF process train.

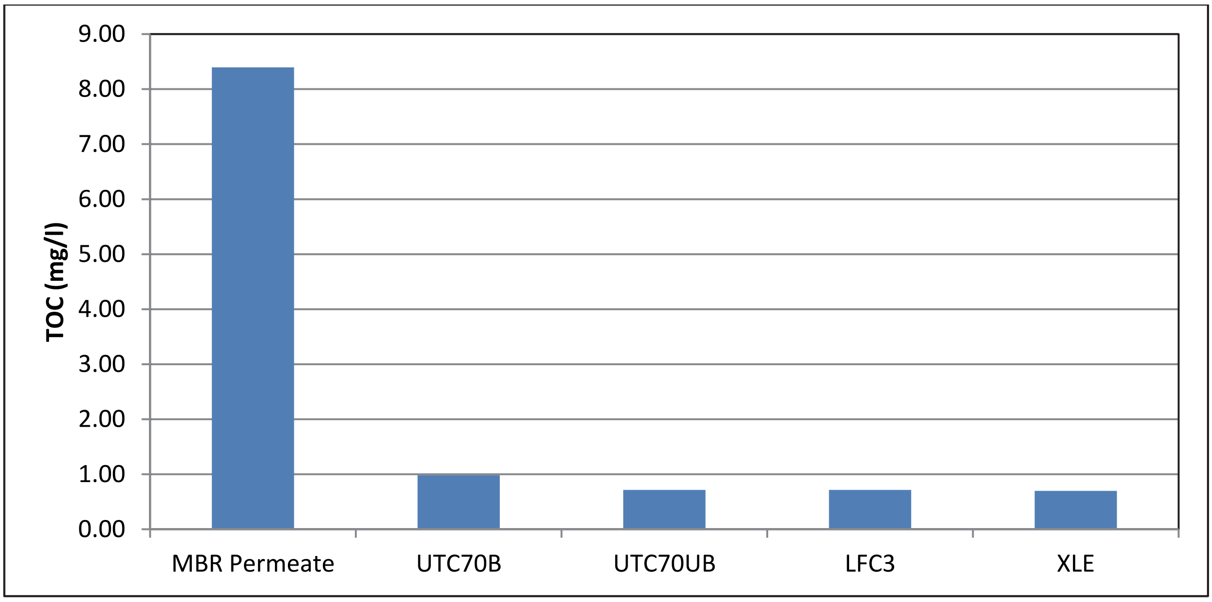


Figure 4.19: Average TOC Levels in the Product Water

4.5.4 Microbial Content

Both coliphages and *E.coli* were removed completed by the RO membranes, with one exception. The Toray (UTC70UB) membrane returned positive E.coli results in the last four samples taken. The turbidity (<0.4 NTU) and TOC (<0.7 mg/l) values recorded on these days suggests there was no breakthrough and that the membrane was intact. This may therefore suggest contamination of some form, of the unit or in the sampling procedure.

4.5.5 Turbidity

Following MBR, the turbidity is reduced to less than 1 NTU. This value is halved to less than 0.5 NTU at the 95th percentile by all the RO membranes, and thus meets the target water quality objective.

4.5.6 Summary

The effectiveness of RO in the removal of undesirable components from wastewater, in the MBR, RO process train has been investigated. Among the considered RO membranes, the XLE from Dow Filmtec displayed the highest rejection efficiencies (99%) in rejection of inorganic solutes, in line with its specification (Table 3.2). Rejection levels were almost equal for organics and the other determinands reported on, for all the considered membranes, with the exception of the XLE membrane from Dow Filmtec, which recorded slightly higher values. From these preliminary investigations, all the RO membranes would appear to perform equally well for the intended purpose of wastewater reclamation.

4.6 PERFORMANCE OF THE MBR–RO SPIRAL WOUND TREATMENT SYSTEM

4.6.1 Water Quality Results

Three spiral wound RO membranes were used in the continuous process trials. Two membranes (TR702540HF and FR702540) were provided by Toray, and one by Dow Filmtec (XLE2521). The XLE membrane was obtained later than the others and, at the time of writing this report, insufficient results were available to report on. The permeate water quality from the MBR-RO spiral wound treatment train is presented in Figures 4.20 and 4.21.

4.6.2 Solute Rejection

The TR702540HF (SR1) and FR702540 (SR2) permeate water quality data is plotted in Figure 4.20. It is clear that performance is very similar in terms of the removal of solutes. All determinands measured were removed to within drinking water limits.

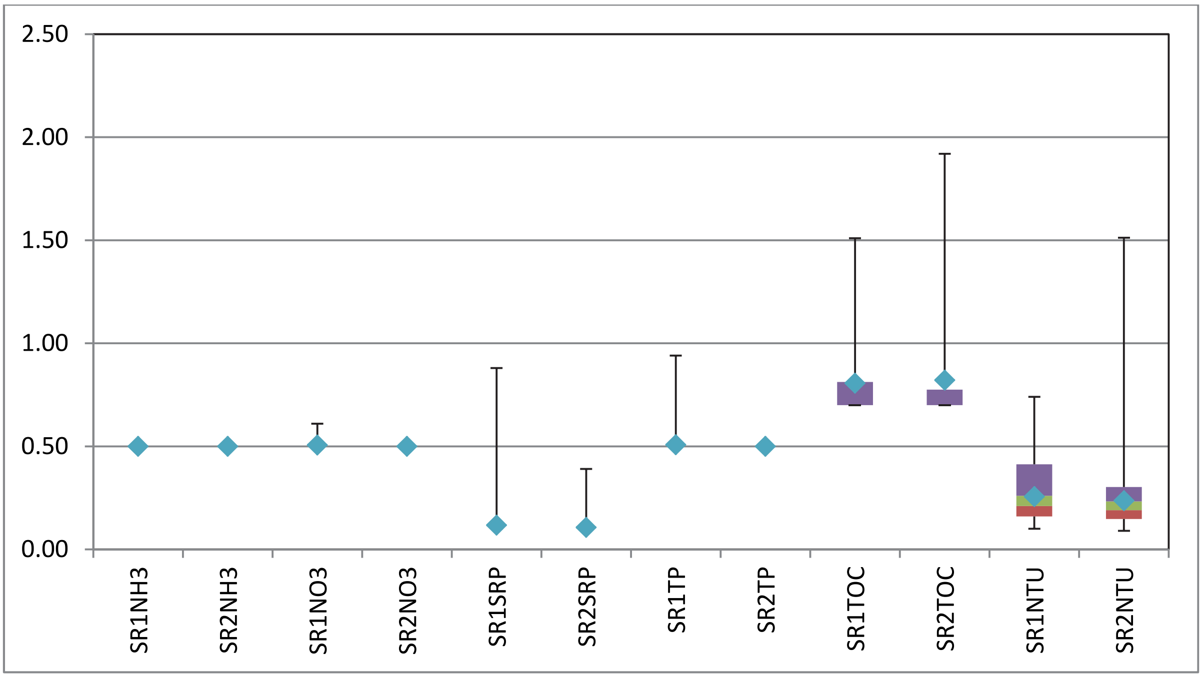


Figure 4.20: MBR-O_3/GAC-RO (Spiral Wound) Permeate Water Quality

Removal of alkalinity and TDS is almost identical (Figure 4.21). High TDS values, above 175 mg/l, are possibly outliers which occurred in the first week of operation while the process was stabilizing. Results obtained from the LC-OCD analyses show that MBR-RO results in a 93% removal of DOC which confirms the TOC results obtained by the Umgeni Water laboratory. The RO membrane reduces DOC concentration to less than 400 ppb (0.4 mg/l).

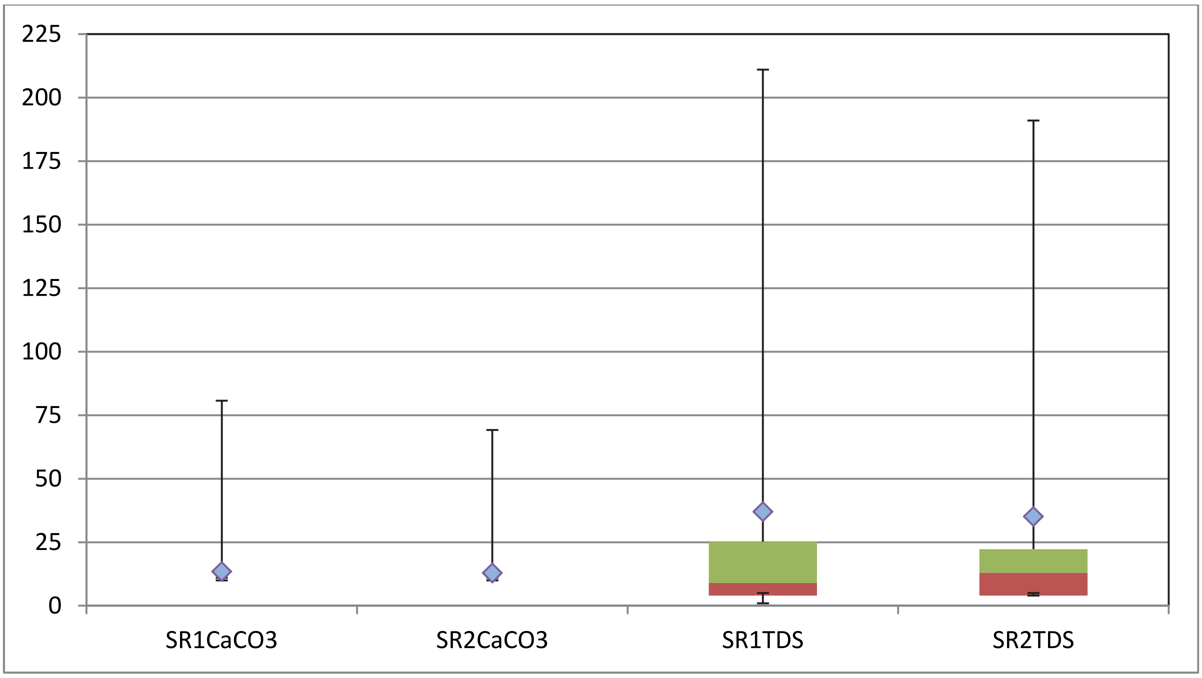


Figure 4.21: MBR-O_3/GAC-RO (Spiral Wound) Permeate Water Quality

4.6.3 Microbial Content

Coliphages and *E.coli* median and mean values were zero in the permeate. Coliforms were recorded in the permeate at 14 and 10 CFU/100 ml at the 95th percentile for SR1 and SR2 respectively. This may indicate some form of contamination during sampling or some contamination in the unit e.g. in the permeate line.

4.6.4 Turbidity

Turbidity at the 95th percentile for SR1 and SR2 was 0.5 NTU and 0.4 NTU respectively.

4.6.5 Summary

The MBR-RO process produces water of potable quality that meets the SANS 241 (2011) drinking water standard.

4.7 THE MBR-RO-UV SPIRAL WOUND WATER QUALITY RESULTS

Trials were initially run without H_2O_2 to ascertain the impact of UV radiation on organic removal. Trials were run at increasing strengths of radiation: 14, 27 and 45 mJ/cm^2. Hydrogen peroxide was then dosed at concentrations of 0.3 and 0.6 mg/l respectively.

4.7.1 UV/H_2O_2 Test Trial 1

Pump Speed (Hz) 45		Flow 2400 l/h		
No of lamps 3 (13.77 mJ/cm^2)		Time for one pass (min) 0.9		
	Raw RO Permeate	After 15 min	After 30 min	After 60 min
UV210	0.191	0.227	0.225	0.226
UV254	0.002	0.006	0.008	0.012
UV280	0.001	0.006	0.006	0.008

4.7.2 UV/H_2O_2 Test Trial 2

Pump Speed (Hz) 65		Flow 4000 l/h		
No of lamps 6 (27.54 mJ/cm^2)		Time for one pass (min) 1.8		
	Raw RO Permeate	After 15 min	After 30 min	After 60 min
UV210	0.152	0.153	0.152	0.158
UV254	0.007	0.008	0.01	0.012
UV280	0.007	0.007	0.008	0.011

4.7.3 UV/H_2O_2 Test Trial 3 (After adding 0.3 mg/l H_2O_2)

	Raw RO Permeate	After 15 min	After 30 min	After 60 min
UV210	0.152	0.884	0.84	0.732
UV254	0.007	0.115	0.106	0.09
UV280	0.007	0.0031	0.0031	0.027

4.7.4 UV/H_2O_2 Test Trial 4 (After adding 0.6 mg/l H_2O_2)

Pump Speed (Hz) 65				Flow 4000 l/h			
No of lamps 10 (45.9 mJ/cm^2))				Time for one pass (min) 3			
	Raw (RO Permeate)	After 15 min	After 30 min	After 60 min	After 90 min	After 120 min	After 180 min
UV210	0.127	0.491	0.437	0.533	0.282	0.229	0.168
UV254	0.003	0.046	0.055	0.034	0.029	0.022	0.014
UV280	0.001	0.014	0.013	0.012	0.011	0.01	0.009

Results obtained from trial 2 (Figure 4.22) and trial 4 (Figure 4.23) are plotted below.

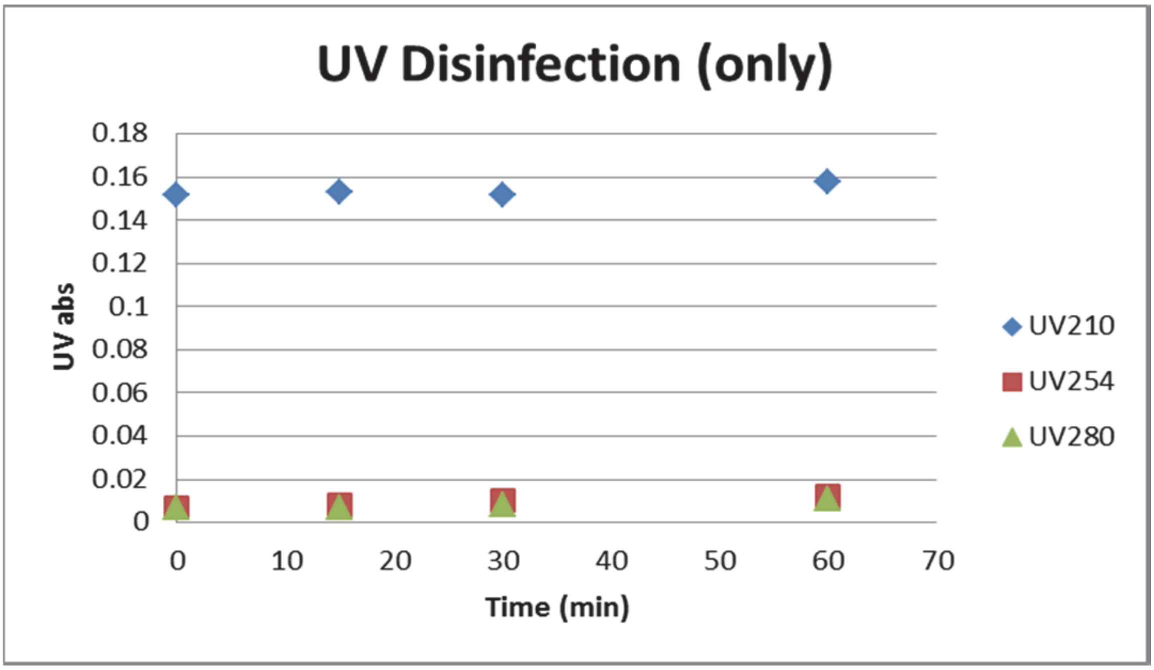


Figure 4.22: UV Disinfection without H_2O_2 Addition (Trial 2)

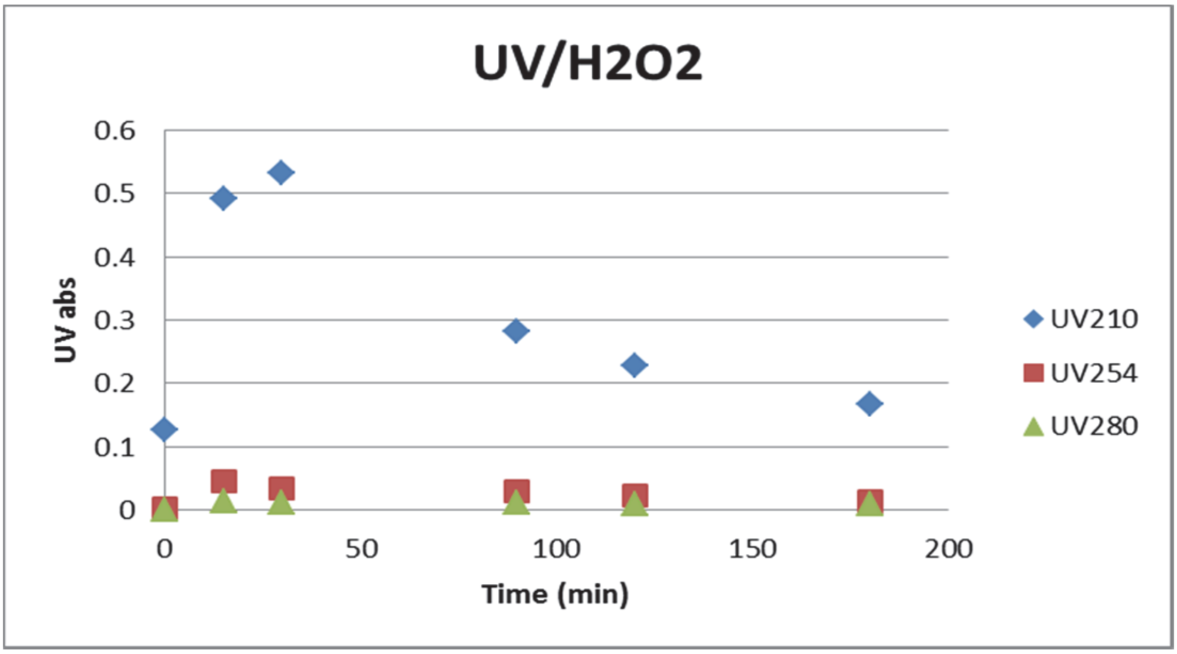


Figure 4.23: UV Disinfection with 0.6 mg/l H_2O_2 Added (Trial 4)

Comparing the graphs above, it can be seen that the UV absorbance is almost constant during UV disinfection alone (Figure 4.22), but with the addition of $H_2O_{2,}$ UV absorbance increases then decreases with time (Figure 4.23). Sodium thiosulphate was used in an attempt to stop the reaction of the residual $H_2O_{2,}$ but the attempt failed as the UV readings shot up drastically after the dosing of sodium thiosulphate.

The increase in UV absorbance is influenced by two factors:

1. The breaking down of large organics to smaller ones (oxidation by H_2O_2)
2. The absorbance of UV rays by H_2O_2.

It can be seen from trials 1 through to 4 that the UV_{254} is well below the water quality objective UV_{254} of 0.065 cm^{-1}. This is because the majority of organics have been removed by the upstream processes and the water is very clean. The effectiveness of the UV/H_2O_2 process in improving water quality was therefore very difficult to measure. The UV/H_2O_2 water quality, after MBR-RO-UV/H_2O_2, was sampled and the water quality results showed no discernible differences with the RO permeate. A decision was therefore made that no further sampling of the UV/H_2O_2 permeate would be undertaken. The UV/H_2O_2 can in the assessment of this study be considered as a precautionary disinfection step (additional barrier) to protect against possible breakthrough of harmful viruses.

4.7.5 LC-OCD Analyses

UV/H_2O_2 samples were also sent to Germany for identification of the carbon molecular weight distribution. A very sensitive separation technique known as Liquid Chromatography–Organic Carbon Detection (LC-OCD) was used. Separation is based on size-exclusion chromatography followed by multi-detection with organic carbon (OCD), UV-absorbance at 254 nm (UVD) and organic bound nitrogen (OND). The additional LC-OCD analyses were necessitated as the RO permeate used as a feed to the UV/H_2O_2 is very clean water. There was therefore no meaningful distinction between the RO permeate water quality results and the UV/H_2O_2 permeate water quality results, because measurement was beyond the Umgeni Water laboratory analysis detection limits. The benefits of contaminant removal using UV/H_2O_2 could therefore not be assessed.

Results obtained from the LC-OCD analyses show that MBR-RO-UV results in a 93% removal of DOC, which confirms the TOC permeate results obtained by the Umgeni Water laboratory (<0.7 mg/l). The RO membrane reduces DOC concentration to less than 400 ppb (0.4 mg/l). This is reduced further by the UV radiation unit process to less than 250 ppb (0.25 mg/l).The UV radiation achieves this by reducing the low molecular weight neutrals. This fraction includes alcohols, aldehydes, ketones and amino acids. UV/H_2O_2 reduces the concentration of organics by approximately 38%.

4.8 ALTERNATIVE PROCESS TRAIN

At the request of the WRC reference group, an alternative treatment train was proposed (MBR-NF-O3/GAC-UV) and laboratory trials were undertaken to compare the performance in terms of the water quality produced. The treatment train proposed that the nanofiltration step precede the O_3/GAC process unit, instead of following it, as was the case in previous tests. In a full scale plant there may be a number of operational advantages to this particular process train. At a laboratory scale these advantages may not always be apparent or calculable. A comparison of the permeate water quality from this train with the other process trains can, however, provide some indication of the relative performance.

The theoretical advantage of this treatment train is that the NF membranes will reduce the organic load onto the O3/GAC unit. This has the advantage of reducing the amount of ozone required to break down complex organic molecules and hence the ozone operating cost should be reduced. Similarly, by reducing the organic load, the life span of the GAC beds should be increased and operating cost reduced through extending the carbon regeneration period.

4.8.1 Solute Rejection

The results obtained (Figures 4.24 and $.25) are comparable to the results achieved by the MBR-O_3/GAC-NF-UV process. Nanofiltration does not remove nitrate and therefore the process is dependent on the activated sludge process in the MBR. As was experienced during the previous operating period, the denitrification process in the MBR was not operating well and nitrate concentrations in the permeate do not meet the water quality objective of below 6 mg/l. There was very little difference in the alkalinity and TDS concentration between the two process trains; average alkalinity (72 mE/l $CaCO_3$) being slightly higher in the MBR-NF-O3/GAC-UV process than the 57 mE/l $CaCO_3$ concentration obtained in the MBR-O_3/GAC-NF-UV process train. TDS permeate concentrations for the MBR-NF-O3/GAC-UV and MBR-O_3/GAC-NF-UV are 219 and 206 mg/l respectively.

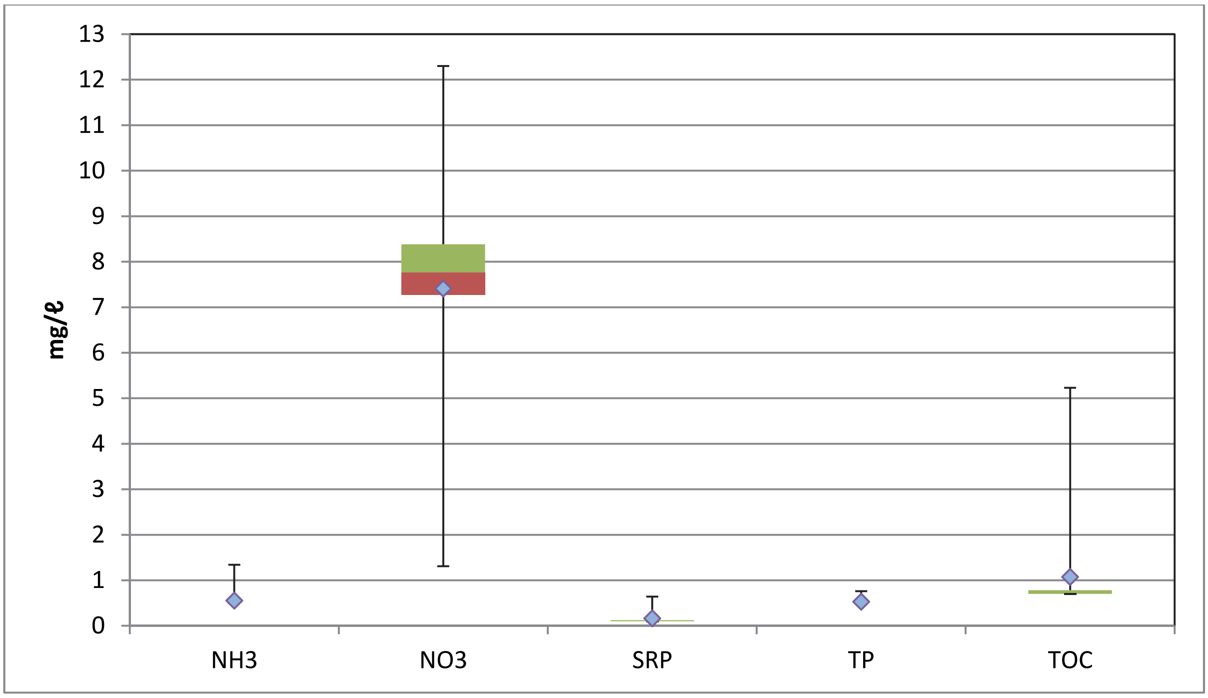


Figure 4.24: MBR-NF-O3/GAC Permeate Water Quality

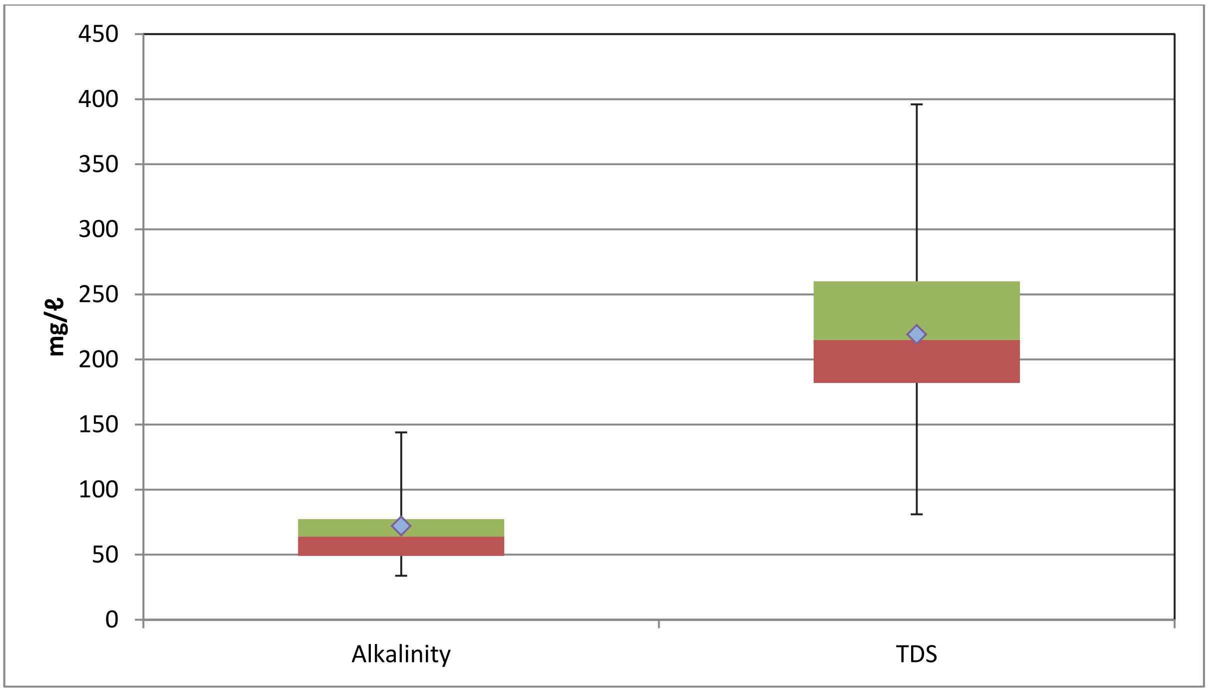


Figure 4.25: MBR-NF-O3/GAC Permeate Water Quality

4.8.2 Turbidity

Average turbidity of 0.25 NTU and 0.41 NTU at the 95th percentile were recorded.

4.8.3 UV_{254}

Average UV_{254} was 0.0048 cm^{-1} and UV_{254} was 0.0060 cm^{-1} at the 95th percentile in the permeate. This is below the water quality objective of 0.065 cm^{-1}.

4.8.4 Microbial Content

Coliphages and *E.coli* median and mean values were zero in the permeate. Coliforms were recorded in the permeate at an average of 78 CFU/100 ml, and at 384 CFU/100 ml at the 95th percentile. UV radiation as the final step in the process will remove excess coliforms but was not run in this trial. The permeate turbidity was < 0.5 NTU and the UV_{254} was < 0.065 cm^{-1}. Both of these measurements indicate clear water with low levels of organic matter present. There should be thus no impediment for the UV radiation to function as designed and remove microbiological content.

4.8.5 Summary

The MBR-NF-O3/GAC-UV process produces water of a potable quality that meets the SANS 241 (2011) drinking water standard, with the exception of nitrate. The permeate quality is very similar to the previously tested MBR-O_3/GAC-NF-UV process. As there is no filtration process after the GAC, the coliform count is relatively high and this is a potential water quality concern. It is, however, expected that the final UV radiation unit process proposed would achieve a zero coliform count. Operationally, by placing the NF upstream of the O_3/GAC unit, the TOC entering the O_3/GAC was reduced from an average 5.8 mg/l to < 1 mg/l. This allowed the ozone dosage to be reduced from 9 mg/l to 6 mg/l. A further reduction in the dosage was not possible due to the difficulty of measuring the required ozone dosage at lower levels (ozone demand). This reduction in ozone consumption would obviously have a major financial benefit at full scale. Similar operational benefits may accrue in increasing the time between carbon regeneration periods, as the substantial reduction in TOC would apply less organic load onto the carbon. No calculation was made of the potential economic benefit derived from placing the NF upstream of the O_3/GAC. This analysis is recommended as part of future research, as it was beyond the scope and time available under the current project.

4.9 EDC REMOVAL RESULTS

4.9.1 Steroid Hormones

The Darvill final effluent and permeate from the advanced water treatment unit processes were analysed for a selection of commonly occurring steroid hormones and antibiotics. The steroid hormones included estrone (E1), 17β-estradiol (E2), estriol (E3), 17α-ethinyl-estradiol (EE2), testosterone and progesterone. Analyses were also carried out for the antibiotics, fluoroquinolones and sulphamethoxazole. Results were obtained for each of the proposed treatment trains and their efficiency in removing these potentially harmful compounds was compared. The removal efficiency of the selected treatment trains for each of these trace organics is illustrated in Figure 4.26. Where possible, given constraints on time and cost, different membranes were used. Hence RO1 and RO2 represent the Toray membranes UTC70B and UTC70UB respectively. The NF membrane used is the SR 90 from Dow Filmtec.

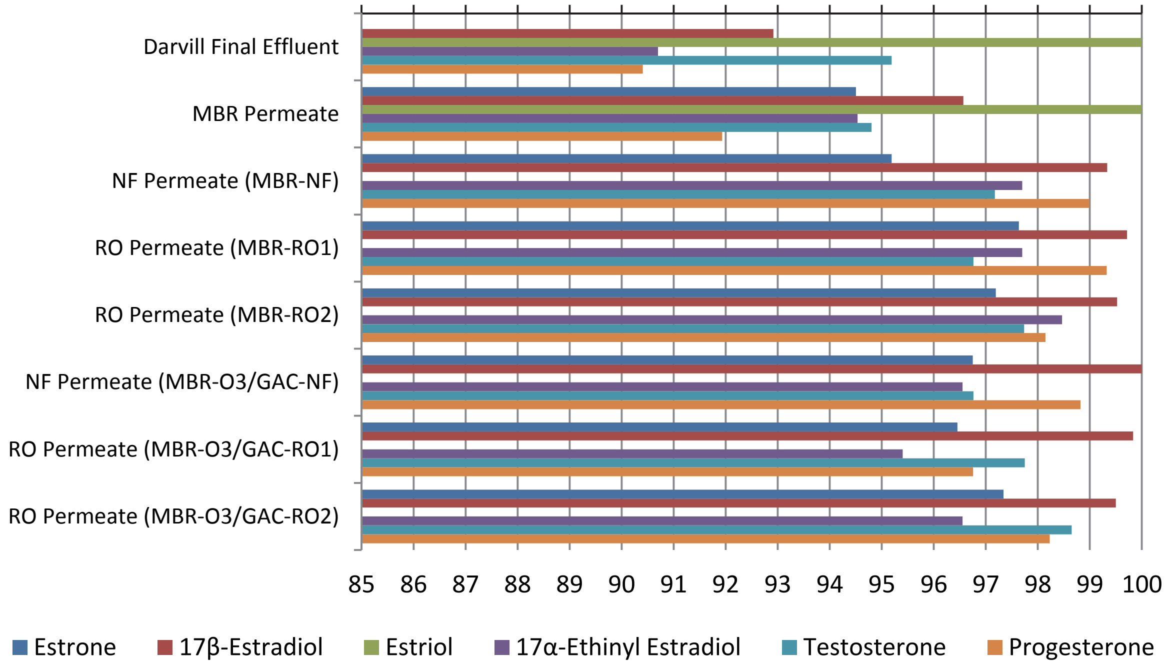


Figure 4.26: Advanced Treatment – EDC (Steroid Hormones) Removal Percentage

The results support a number of findings and these are elaborated on below:

- It is evident that conventional treatment is effective at removing a significant proportion of trace organics, with all the hormones being removed by 90% or more.
- The MBR generally outperforms conventional treatment. There are a number of reasons, including longer sludge residence times, that contribute to this, and these reasons are discussed in detail by various authors (US Bureau of Reclamation, 2009).
- The lowest average removal rate was achieved by the MBR-NF process train which removed only 94% of estrone. This average result was possibly distorted by an unusually high reading in one of the permeate results. Further testing should be undertaken to establish if this was an exception.
- All the treatment processes are effective at removing the trace organics with no significant difference being apparent in the results.
- NF appears to be as effective as RO, which is unexpected and is not supported by other research (US Bureau of Reclamation, 2009).
- There appears to be limited benefit from the O_3/GAC process in removing steroid hormones, with the MBR-NF and MBR-RO processes performing equally well, without these unit processes. This is confirmed by the removal percentage achieved by the ozone and GAC processes (Table 4.8), which range from 5 -79%. Progesterone was most effectively removed by ozonation (78%) and GAC (79%).

Table 4.8: Advanced Treatment – EDC (Steroid Hormones) Removal Percentage

% Removal	**Estrone**	**Estradiol**	**Estriol**	**17α-Ethinyl Estradiol**	**Testosterone**	**Progesterone**
Darvill Final Effluent	73.9	92.9	100	90.3	94.8	89.5
MBR Permeate	94.5	96.6	100	94.3	94.3	93.2
Post Ozonation	19.4	53.5	-	28.6	53.1	78.2
GAC Permeate	30.0	58.3	-	66.7	5.3	79.2
NF Permeate (MBR-NF)	94.4	99.2	-	98.0	97.3	98.9
RO Permeate (MBR-RO1)	97.6	99.7	-	98.0	96.9	99.3
RO Permeate (MBR-RO2)	97.2	99.5	-	98.7	97.8	98.1
NF Permeate (MBR-O_3/GAC-NF)	96.8	100.0	-	97.0	96.9	98.8
RO Permeate (MBR-O_3/GAC-RO1)	96.5	99.8	-	96.0	97.8	96.6
RO Permeate (MBR-O_3/GAC-RO2)	97.3	99.5	-	97.0	98.7	98.1

The removal of steroid hormones by the O_3/GAC (table 3.8) appears to be far lower than in the research reported by Snyder et al. (2007) that demonstrated that GAC was capable of providing greater than 90% removal of nearly all compounds. This may be partially due to the fact that the removal percentages for the GAC are calculated using the ozone permeate concentration as the feed. The concentration of organic contaminant remaining after ozonation is usually very small and therefore the percentage removal by the GAC is small. For example, if percentage removal by the O_3/GAC was calculated using the MBR permeate concentration, the removal for steroid hormones is 43–96% and for antibiotics 94–95%. These results more accurately reflect those obtained by Snyder et.al. (2007).

4.10 ANTIBIOTICS

Further testing was undertaken to determine the efficiency of the processes in removing other compounds such as antibiotics. The use of antibiotics is ubiquitous in society today and thus the likelihood of these substances occurring in wastewater is considered high. Fluoroquinolones represent a group of substances that are known to be found on a regular basis in wastewater. Similarly, sulfamethoxazole is also a commonly used antibiotic. Results of testing for their occurrence in Darvill wastewater, and the efficiency of their removal by the selected treatment processes, are presented in Figure 4.27.

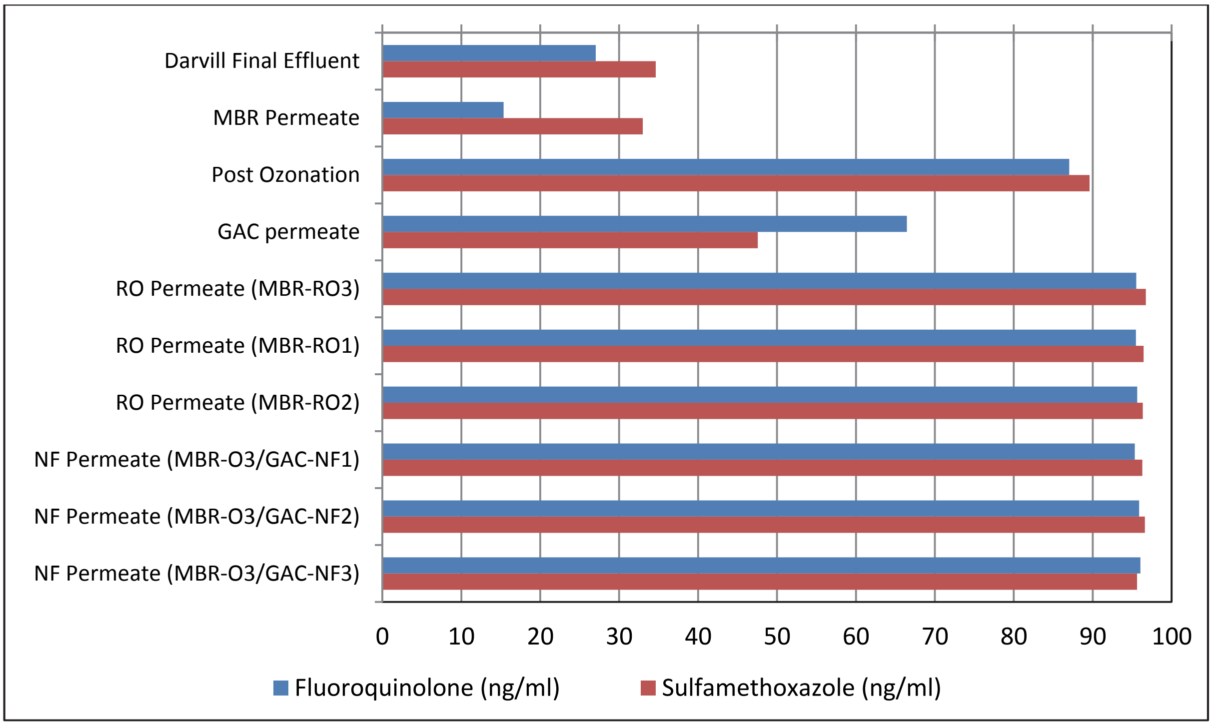


Figure 4.27: Advanced Treatment – EDC (Antibiotics) Removal Percentage

The results support a number of findings and these are elaborated on below:

- It is apparent that activated sludge, whether conventional or in an MBR, is ineffective at removing these particular antibiotics (<35% removal).

- Ozonation appears to be very effective at removing both compounds (>87% removal).
- Absorption by GAC removes 47% sulphamethoxazole and 66% fluoroquinolones.
- The relative performance of the selected treatment trains appears very similar. All remove the antibiotic compounds to > 95%.
- There appear to be only small differences in performance between the various membranes, both RO and NF.

4.11 EDC SPIKING

Two solutions, of 200 ng/l and 1,000 ng/l, of three steroid hormones (estrone, 17α-ethinylestradiol, testosterone) were made up in the Umgeni Water laboratory. The trace organic concentrate was ordered from a commercial laboratory. The EDC standards made up were decanted into the MBR permeate 1,000 litre tank from where it was automatically pumped to downstream processes. The process trains were spiked to determine the impact of high concentrations of contaminants that may occur on full-scale plants as a result of pollution. The results are plotted in Figure 4.28. The level of spiking was based on the average concentrations found in Darvill settled sewage multiplied by five times to mimic possible worst case scenarios.

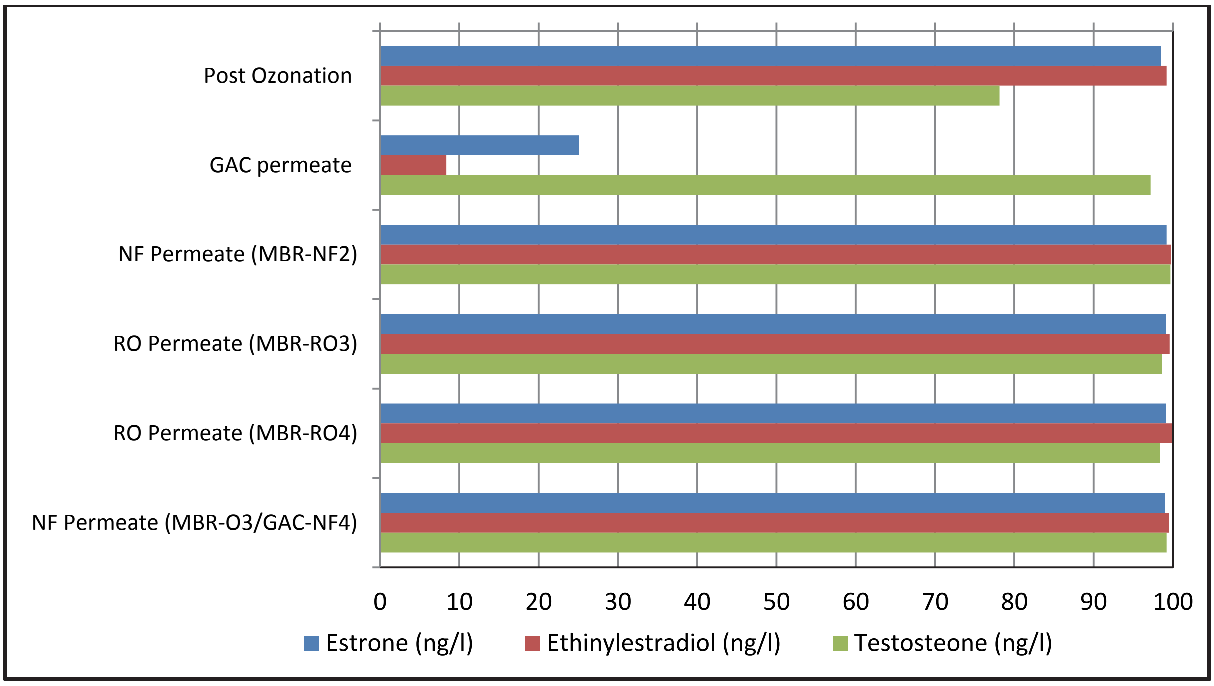


Figure 4.28: EDC (200 ng/l) Spiking – Removal Percentage

The 200 ng/l spiking results illustrated the following:

- Oxidation by ozone removed estrone and ethinylestradiol (98–99%) and testosterone (78%). These results are supported by those reported by Westerhoff et.al. (2005), where ozone 70tabiliz steroids containing phenolic moieties (estradiol, ethynylestradiol, or estrone) more efficiently than steroids without aromatic or phenolic moieties (androstenedione, progesterone, and testosterone).

- The GAC was poor at removing estrone and ethinylestradiol, but was very effective at removing testosterone.
- The specified process trains were all very successful in removing the trace organic contaminants, with most achieving removals above 99%.
- There appeared to be no discernible difference in water quality based on the type of membrane used; the NF membranes performed as well as the RO membranes.

The number of samples taken was increased for the 1,000 ng/l spiking trials so that the removal efficiencies of each of the individual unit processes could also be assessed. For this trial, the GAC permeate was spiked as well as the MBR permeate, to mimic the situation of contaminant breakthrough. The results obtained are shown in Figure 4.29.

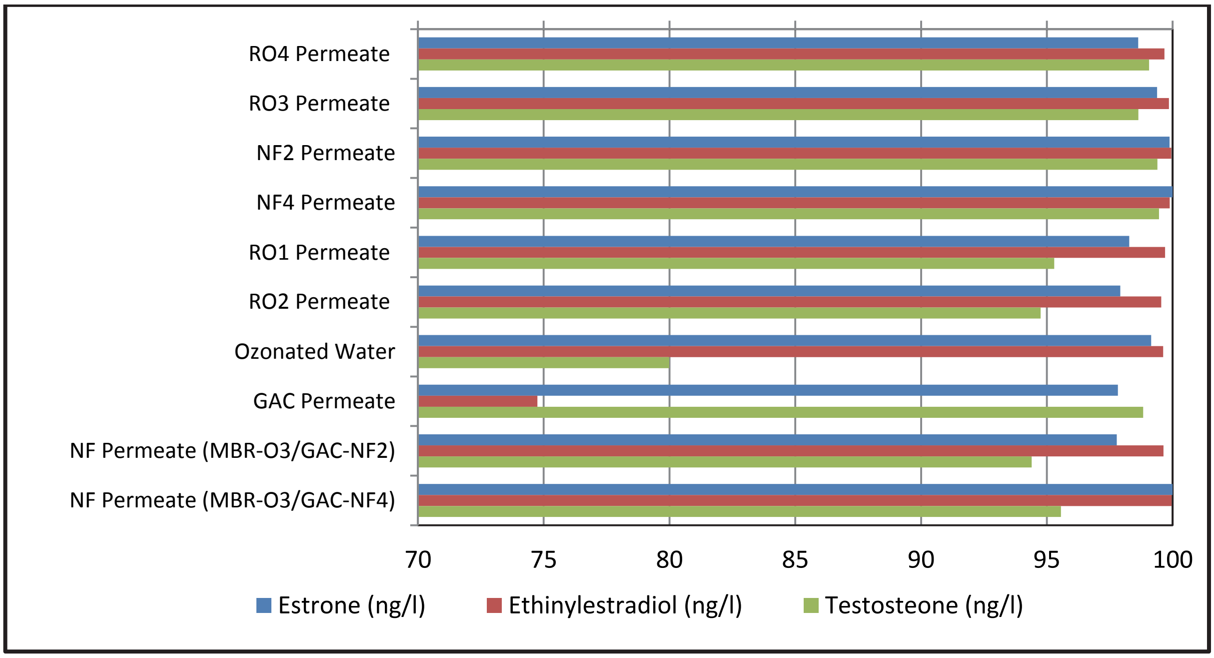


Figure 4.29: EDC (1,000 ng/l) Spiking – Removal Percentage

The 1,000 ng/l spiking results illustrated the following:

- Oxidation by ozone removed estrone and ethinylestradiol (99%) and testosterone (80%). As stated previously, these results are supported by those reported by Westerhoff et.al. (2005) where ozone 71tabiliz steroids containing phenolic moieties (estradiol, ethynylestradiol, or estrone) more efficiently than steroids without aromatic or phenolic moieties (androstenedione, progesterone, and testosterone).
- The GAC was effective in removing both estrone and testosterone. It was less effective in removing ethinylestradiol, which was the case in the 200 ng/l spiking test.
- All the NF and RO membranes were very effective (>97%) at removing estrone and ethinylestradiol. All the membrane types removed testosterone less effectively, however; only the NF2 and RO2 membranes achieved a testosterone removal rate greater than 95%. The average removal efficiency

achieved was lower than for the 200 ng/l EDC spike which recorded an average 99%, compared to 97% for the 1,000 ng/l EDC spike.

- The average removal efficiencies for estrone (99%) and ethinylestradiol (99.7%) were the same for both spiking experiments, indicating that the NF and RO membranes can cope with potential pollution spikes or breakthroughs from upstream processes.

The spiking trials confirmed that the tested treatment processes were equally effective at removing EDCs, even when their concentrations were five times the normal concentrations recorded in the Darvill raw wastewater influent.

4.12 REMOVAL OF TRACE ORGANICS BY ADVANCED OXIDATION

The advanced oxidation pilot tests were conducted with pre-treated (MBR-RO) wastewater. Hydrogen peroxide was dosed into the feed water (MBR-RO permeate) upstream of the UV radiation unit. An H_2O_2 concentration of 5 mg/l was dosed, with varying intensities of UV radiation, in a number of trials, to determine the impact of these changes on trace organic removal. The feedwater was spiked with two EDCs (estrone and testosterone) at concentrations as high as 2,000 ng/l. The results of these trials are detailed in Table 4.9 and the percentage removals are given as log removal values (LRV).

Table 4.9: Advanced Oxidation – EDC (Steroid Hormone) Removal

UV Dose (mJ/cm^2)	H_2O_2 Dose (mg/l)	EDC Spike (µg/l)	Estrone (µg/l)	LRV	Testosterone (µg/l)	LRV
50	0	10	0.0098368	3.01	0.017	2.8
100	0	10	0.0028268	3.55	0.006	3.2
200	0	10	0.0017462	3.76	0.005	3.3
50	0	150	0.0439114	3.53	0.133	3.1
100	0	150	0.0376283	3.60	0.128	3.1
200	0	150	0.0296177	3.70	0.093	3.2
50	0	2,000	0.0562038	4.55	0.154	4.1
100	0	2,000	0.076898	4.42	0.144	4.1
200	0	2,000	0.0525207	4.58	0.070	4.5
50	5	10	0.0017363	3.76	0.015	2.8
100	5	10	0.001718	3.76	0.010	3.0
200	5	10	0.0011839	3.93	0.008	3.1
50	5	150	0.0384895	3.59	0.140	3.0
100	5	150	0.0336729	3.65	0.129	3.1
200	5	150	0.033341	3.65	0.107	3.1
50	5	2,000	0.0621717	4.51	0.143	4.1
100	5	2,000	0.0437341	4.66	0.170	4.1
200	5	2,000	0.0361066	4.74	0.139	4.2

The LRVs achieved for both estrone and testosterone at all spiked concentrations were > 3.0. Figures 4.30–4.32 illustrate the impact of dosing H_2O_2 and increasing the UV intensity from 50 to 200 mJ/cm^2. The figures presented illustrate the following:

- At a trace organic spiked concentration of 10 µg/l (Figure 4.30) the log removal efficiency for both estrone and testosterone increases with increased UV dose, without the addition of H_2O_2. Similarly, the removal efficiency increases with increased UV dose with the addition of 5 mg/l of H_2O_2.
- There is a marked improvement in the removal efficiency of estrone with the addition of 5 mg/l of H_2O_2 at a UV dose of 50 mJ/cm^2. This is probably due to the creation of a greater concentration of hydroxyl radicals to assist in the oxidation process. The improvement in performance with the addition of H_2O_2 is not as evident at higher UV doses.
- Unexpectedly, the opposite trend is evidenced in the removal efficiency of testosterone with the addition of 5 mg/l of H_2O_2. The trend is reversed and the removal efficiency decreases with increased UV dose.
- At trace organic spiked concentrations of 150 µg/l (Figure 4.31) and 2,000 µg/l (Figure 4.32) the same result is evident. There is a decrease in removal efficiency with the addition of 5 mg/l of H_2O_2. This may suggest that the addition of H_2O_2 is negatively impacting on the UV radiation performance and that the H_2O_2 is absorbing or scattering UV radiation.

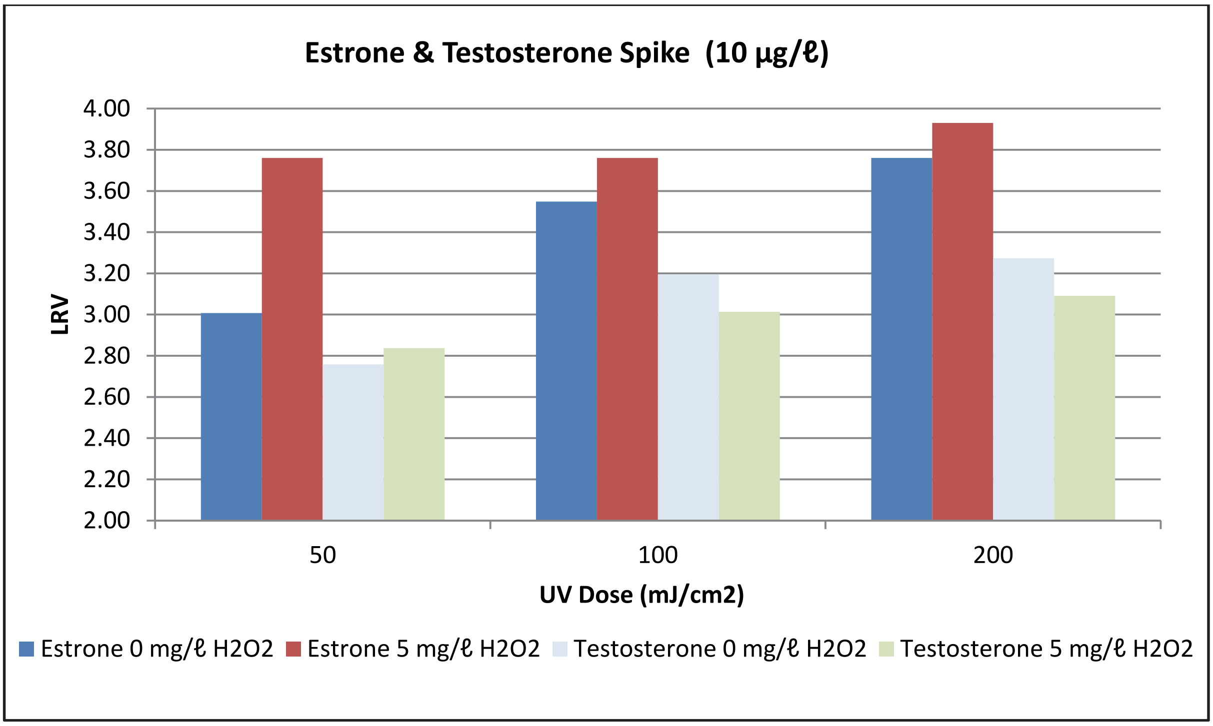


Figure 4.30: Removal of EDCs (10 µg/l) by Advanced Oxidation

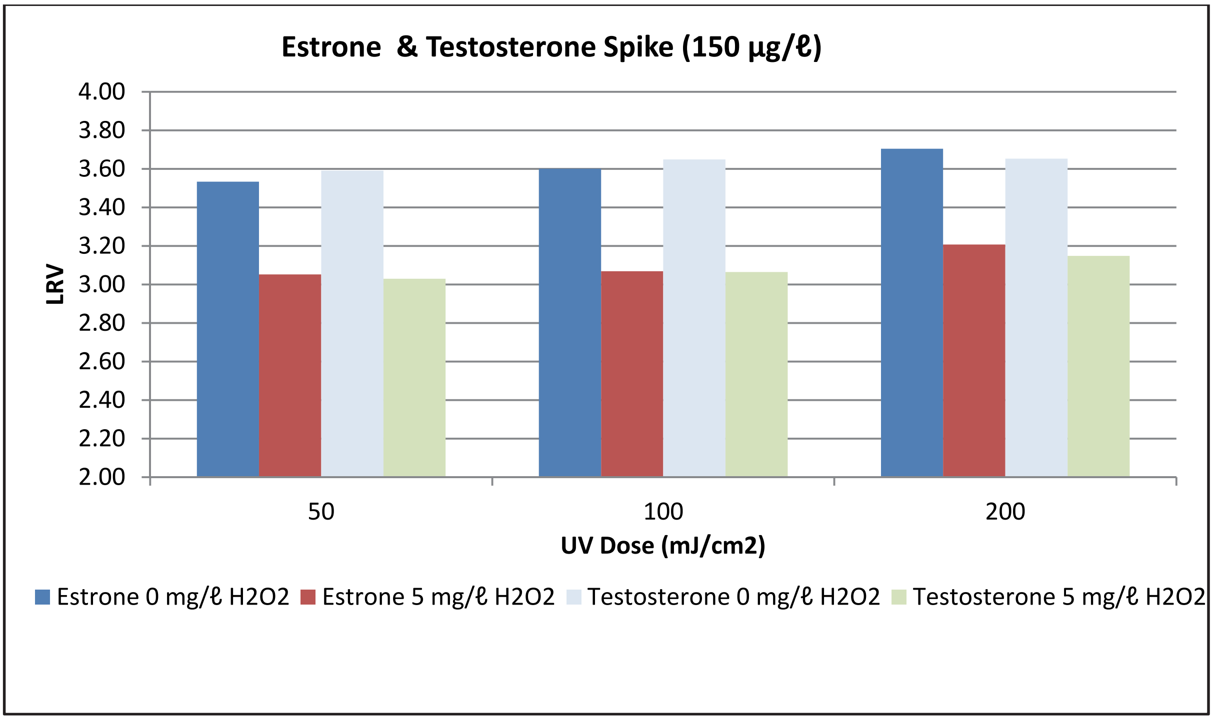


Figure 4.31: Removal of EDCs (150 µg/l) by Advanced Oxidation

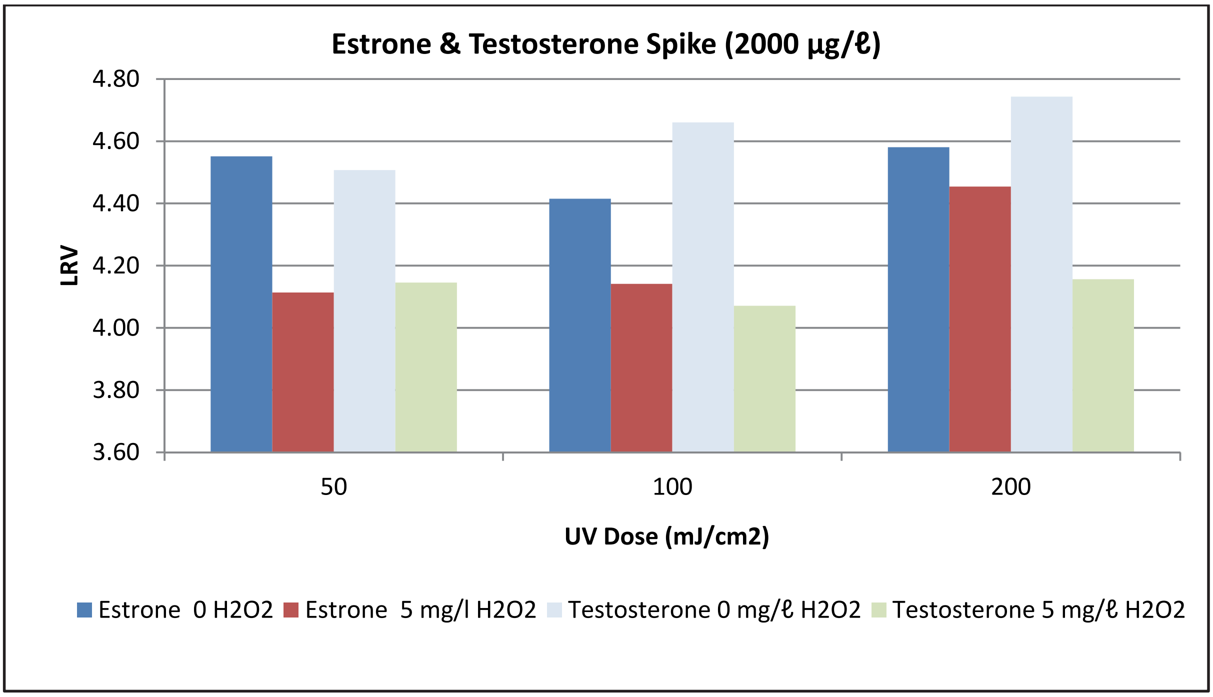


Figure 4.32: Removal of EDCs (2,000 µg/l) by Advanced Oxidation

For reclaimed water systems, the recommended design UV dose is 50 mJ/cm^2 for reverse osmosis effluent. The dosage is intended to provide 4 logs of polio virus inactivation with a factor of safety of about 2. In addition, for RO effluents, the design transmittance is 90 per cent.

From the results presented here it is noticeable that only a marginal improvement is obtained in LRV at the higher UV dosages of 100 and 200 mJ/cm^2. The extra capital and operating expense of UV equipment capable of dosing at these higher radiation levels may therefore not be justified. Similar observations are reported by Snyder et al. (2003), who demonstrated diminishing returns with large increases in UV and H_2O_2 doses, suggesting that lower doses may provide nearly equivalent contaminant reduction with less energy and peroxide cost.

When EDCs were spiked at 2,000 µg/l the dose of 50 mJ/cm^2 proved to be extremely effective in achieving LRV > 4 or 99.99% removal. This confirms indicative per cent removals reported in Table 2.1, where advanced oxidation removes > 80 % of steroid hormones. The addition of H_2O_2 proved not to be as effective as reported in other research (US Bureau of Reclamation, 2009) and unexpectedly had the opposite effect, decreasing the removal efficiency.

Advanced oxidation as evidenced by these results is highly effective at removing the steroid hormones estrone and testosterone, confirming research undertaken previously (US Bureau of Reclamation, 2009). Advanced oxidation therefore represents an effective final treatment barrier in the proposed reclamation process treatment train.

4.13 SUMMARY

The results show that advanced treatment technologies are very effective at removing contaminants such as trace organics, to very low levels. Contaminants are removed at > 95% in each of the selected treatment trains. Contaminants often occur at greater levels in treated potable drinking water despite rather stringent regulations regarding disinfection and residual disinfectant in distribution systems (Snyder and Benotti, 2010), because the level of treatment is not as rigorous. Consumers are also more likely to receive far higher dosages of certain contaminants through the external environment and from their food sources than from drinking reclaimed water (Stanford et al., 2010).

The organic contaminant levels recorded in this research are so low that only the most sophisticated of analytical laboratory techniques can detect them. The contaminants are, however, still detectable in some cases, in extremely small concentrations e.g. ng/l. The WHO does not consider contaminants at this concentration to be harmful if consumed in drinking water (2008). Concerns still remain, however, over the possible cumulative or synergistic impact of these contaminants (US Bureau of Reclamation, 2009; Kumar & Xagoraraki, 2010). For this reason, many experts are proponents of the multiple-barrier approach which ensures that more than one unit process exists in the treatment train for each set of contaminants.

The experimental results suggest that streamlined process trains such as MBR-RO (replicating the Singapore process) or MBR-NF-UV, are equally effective as treatment trains with additional processes, such as ozonation and GAC (MBR-O_3/GAC-NF). Ozonation and GAC have proven to be effective barriers to CECs from the results achieved in this study and other research, and therefore they do offer added security and an additional barrier if the engineer wishes to include them.

Although the advanced oxidation unit process was only batch tested during these trials, at full scale this process will be added to each of the selected process trains. This will have the advantage of adding another barrier and additional protection against the passage of contaminants. As previously described and demonstrated by batch experiments undertaken, advanced oxidation is effective at removing a host of organic contaminants as well as providing disinfection for bacteria and viruses. Hydrogen peroxide / UV radiation is the most common advanced oxidation process used in reclamation and has the benefit of reducing the use of chlorine which is known to increase the possibility of disinfection by-products.

CHAPTER 5: CONSIDERATIONS FOR WATER RECLAMATION PLANT DESIGN

5.1 BASIS OF DESIGN

The successful schemes presented in the literature review provide a benchmark for the design of future indirect and direct potable reclamation schemes. Although similar in many respects, the schemes use different technologies or combinations of technologies to achieve the same objective and it becomes difficult to justify which process train is the most suitable. When choosing a process train a number of factors need to be considered, including: feed water quality, treatment objectives, capital and operating cost and final water quality.

Four DPR treatment trains have been tested in this project, namely:

- Process A: MBR-RO-UV
- Process B: MBR-O_3/GAC-NF-UV
- Process C: MBR-NF-O_3/GAC-UV
- Process D: MBR-NF-UV
- Process E: MBR-O_3/GAC-UF-UV

Process E was not initially included in the study, but has been subsequently included based on the research findings. All four trains performed equally well in terms of the final potable water quality produced. Although there were minor differences in product water quality between the processes, all four are compliant with the SANS 241 (2011) drinking water standard. The inclusion of two oxidation processes (ozonation and AOP (UV/H_2O_2) in processes B & C is for synergistic purposes and not merely a conservative design approach. While both unit processes have a number of treatment benefits, ozone is principally applied for oxidation of trace organics and UV is applied for disinfection. The synergistic benefit is that the ozone provides additional disinfection and increases the water's ultra-violet transmittance, both of which will reduce the required UV dosage and thus reduce power requirements (Schimmoller et al., 2010).

A major project objective is to determine the most economical DPR process train that can produce drinking water of potable quality. High level pre-feasibility cost estimates have therefore been calculated for processes A & B. A capital cost estimate was not calculated for process C as the cost was considered to be approximately the same as that for process B at this level of detail. There may be operating cost advantages of process C compared to process B but determining these was beyond the scope of this project.

The capital cost for process D (using NF) was not calculated, as process A (using RO) was considered a more appropriate design for the following reasons:

- NF membranes are more expensive than RO membranes.
- New ultra-low pressure RO membranes are now available and therefore the difference in operating pressure has narrowed and the electricity cost saving of using NF has reduced.
- Higher salt rejection is achievable with RO membranes making the brine more concentrated and thus more economical to treat if oceanic disposal in not an option.
- Due to the higher rejection, RO tends to require less membrane area than NF, which in turn lowers initial capital cost and the membrane replacement budget. This may offset the lower operating pressure of NF.
- RO membranes have a proven track record in wastewater reclamation giving them an advantage in terms of their perceived reliability and safety compared to NF membranes.
- RO membranes provide a more complete barrier to organic contaminants e.g. trace organics than NF membranes. RO membranes also remove nitrate, which NF membranes do not, making the reclamation plant less reliant on the performance of the secondary biological treatment process to remove nitrate.

Process Options A and B can be broadly described as:

- A membrane-based process treatment train (process A)
- An ozone/granular activated carbon treatment train (process B)

The membrane-based treatment train can to a large degree be considered a replica of two well-known wastewater reclamation plants, namely NEWater in Singapore and OCWD in California. Both these processes use a combination of MF/UF-RO-UV. The MF/UF component of these processes is replaced by an MBR in process option A for the Darvill design. Process option B is modeled on the ozone/granular activated carbon treatment train of the Goreangab treatment process in Windhoek.

In setting the treatment objectives for a DPR treatment train the following need to be considered:

- feed water quality
- contaminant removal e.g. CECs
- final water quality.

To ensure the quality of the final product water and the safety of consumers it is advisable to have multiple treatment barriers. Two or more barriers should be defined for each water quality parameter or contaminant, so that a high level of safety is built into in the process. Table 5.1 lists water quality parameters and identifies the associated treatment barriers. The MBR process functions as two treatment processes combined, namely; activated sludge and ultrafiltration. The activated sludge component of the MBR process is responsible for nutrient removal and the ultrafiltration for phase separation.

Table 5.1: Treatment Barriers

Water Quality Parameter	**Treatment Barrier**	
	Process A	**Process B**
Suspended Solids	3 = MBR, RO	4 = MBR, GAC, NF
BOD / COD	3 = MBR, RO	4 = MBR, GAC, NF
Nutrients (N,P)	2 = MBR, RO*	2 = MBR, NF*
Microbiological	4 = MBR, RO, UV	5 = MBR, O_3, NF, UV
Salinity/Inorganic	1 = RO	1 = NF
Metals	3 = MBR, RO	3 = MBR, NF
Micro-organics	4 = MBR, RO, UV	4 = MBR, O_3, GAC, NF, UV

NF/RO* partial barrier

It is noteworthy that with the exception of salinity all the other water quality parameters have two or more treatment barriers. The removal of salinity by RO is in fact unnecessary in water with a low TDS such as that encountered at Darvill. NF and RO provide a partial barrier to nitrogen. Integrating MBR, RO and AOP technologies within a multiple-barrier approach for potable reclamation schemes, provides a robust treatment train with numerous advantages over other conventional treatments that treat water from secondary effluents. MBRs provide enhanced removal capabilities for organic matter, nutrients and also CECs. MBRs also deliver high quality feed to a more restrictive RO barrier. The RO step ensures ultimate pathogen removal and almost complete organics removal The AOP provides the additional barrier of CECs' mineralization as a final polishing step. AOP applications benefit from the lower organic content and turbidity from an MBR permeate, as well as from the extremely high liquid transmittance and almost absence of salts after the RO step (Gasull et al., 2014)

Trials using process E (MBR-O_3/GAC-UF-UV) are currently being undertaken and it is hoped that these will continue after the completion of this project. The AOP (UV/H_2O_2) unit process has been decommissioned and is not part of the tests. Preliminary water quality results taken after the UF membrane are good, as would be expected, as the treatment train is the same as for process B (MBR-O_3/GAC-NF-UV). Of particular interest is the final TOC concentration which is < 3 mg/l. This result is significant as a TOC of < 3 mg/l is the set water quality objective for the New Goreangab Water Reclamation Plant.

If the Goreangab TOC standard can be met by process E (MBR-O_3/GAC-UF-UV) then this process train has great potential to be used for the reclamation plant at Darvill WWW. On a full scale plant, the inclusion of AOP and final chlorination will add additional barriers and factors of safety to the process.

5.2 OTHER CONSIDERATIONS

The design and operation of any reclamation scheme should not be planned and managed in isolation and must take into account a host of other factors. Some of these include:

- environmental factors
- the operating philosophy of the existing wastewater (2nd) treatment works
- buffer storage
- monitoring.

As far as possible the quality of influent (wastewater) entering the wastewater treatment works should be controlled. Thus discharges to sewers must be regulated and the regulations enforced, to ensure that there are no unnecessary disruptions to the secondary treatment process. Industrial effluents must be treated onsite as far as possible or be disposed of within the by-laws of the municipality.

The operating philosophy of the secondary treatment works needs to be geared to providing an appropriate quality effluent to the reclamation plant. The works needs to be operated as an integrated system as any disruptions or negative impacts on the secondary treatment works will affect the reclamation process.

It is advisable to include additional buffer storage after the secondary treatment works to ensure disruptions in effluent quality can be identified and appropriate action taken. Similarly, a buffer on the potable side of the reclamation plant enables additional retention time to enable quality control before release into the distribution system.

Finally, monitoring provides additional protection against failure. Source water, process and treated water should all be monitored hourly, daily and weekly depending on the objectives. The use of online process monitoring is standard practice and should be used as a first barrier to potential changes in water quality. It must, however, not be totally relied upon because of the risk from instrument failure.

5.3 UNIT TREATMENT PROCESS SIZING

5.3.1 Process A: MBR-RO-AOP (H_2O_2/UV)

5.3.1.1 Membrane Bioreactor

The MBR process sizing was calculated by Koch Puron (Annexure B-E) based on the information provided by Umgeni Water. This included feed water quality, average and peak wastewater work flows and product water quality requirements. The Koch Puron design is based on their patented UF Puron membranes which are immersed hollow fibre (out to in) single header membranes. The average or sustainable flux had previously been calculated during the pilot plant testing at 17 lmh for an immersed Toray (outside-in) flat sheet membrane. The flux rates achievable with immersed hollow fibre Puron membranes are much higher and a gross flux rate of 25 lmh and a net flux of 21 lmh were selected.

A membrane surface area of approximately 238 000 m^2 will be required to achieve a peak output of 120 Ml/day at a net flux of 21 lmh. The design allows for an N-1 configuration with 12 trains, with 1 train offline for routine maintenance or cleaning. The key design parameters include the net flux, membrane area per module and number of modules.

- Total installed membranes surface: 237,600 m²
- Number of filtration lines: 12 (N-1)
- Modules per filtration line: 11
- Number of modules: 132 (12 trains x 11 modules per train)
- Module area: 1,800 m² per unit (PSH 1800-44 from Koch Membranes)
- Design continuous operational net flux : 21 lmh
- Water depth : 3.0 meters
- Design MLSS concentration: 8.5 g/l
- Blower design flow : 9680 Nm³/h.

Submerged membranes operate at a suction pressure of between 0.3–0.5 bar. For the purposes of estimating power consumption, the upper end of power consumption operating at 0.5 bar was used. Puron operate an RAS recycle of 4:1. In normal operational mode, aeration is applied for between 25–50% of the operational time at a rate of 0.133–0.3 $Nm^3/(m^2h)$.

5.3.1.2 Reverse Osmosis

The RO process sizing was calculated using the Toray DS2 reverse osmosis design software, the results of which are provided in annexure B-F. The key design parameters include the maximum flux, number of membranes per module and number of modules.

- Total installed membranes surface: 199,800 m²
- Membrane area: 37 m^2
- Number of membranes elements: 5,640
- Number of vessels: 940 (6 elements per vessel)
- Module area: 1,500 m² per unit (TML20D-400 from Toray Membranes)
- Design continuous operational net flux : 16 l/m²h
- Recovery: 88%
- Salt rejection: 99.7%.

A multi-stage RO system, comprising three stages, proved to be the required configuration to achieve the desired process efficiencies and product water quality. A low fouling brackish water RO element (TML20N-400) from Toray was used. Mechanical and electrical capital costs are based on the equipment suppliers' recommendations from available raw water data. The cost estimate covers core membrane equipment; intermediate, chemical and CIP tanks; extra piping and valves; motorized equipment and pumps; additional electrical and instrumentation required to operate the system. At 88% recovery, approximately 12 Ml/day of brine with a TDS concentration of 3,776 mg/l will be produced.

5.3.1.3 Advanced Oxidation Process (UV/H_2O_2)

When using RO as part of the treatment process train upstream of UV disinfection, the following performance criteria apply (NWRI, 2012):

- The design UV dose shall be at least 50 mJ/cm^2 under maximum day flow.
- The effluent turbidity shall be equal to or less than 0.2 NTU 95 per cent of the time, not to exceed 0.5 NTU.
- The permeate UV transmittance shall be 90 per cent or greater, at 254 nm.

When using RO for filtration, at least 2 log10 of viruses will be removed through the RO process. 3 log 10 inactivation of polio virus can be achieved with a UV dose of about 30 mJ/cm^2; therefore, a design UV dose of 50 mJ/cm^2 is suggested to account for variability in the effluent quality. Using AOP can reduce the chlorine dose applied for final disinfection, thereby decreasing the levels of DBPs formed. The capital cost information from existing UV plants was used to calculate a cost estimate.

5.3.2 Process B: MBR-O_3/GAC-NF-AOP (H_2O_2/UV)

5.3.2.1 Ozonation

Ozone addition will precede the GAC filtration process and will be introduced as a gas into contact tanks. Specialized ozone generating equipment is used to generate ozone from air. Any remaining ozone requires an off-gas treatment to comply with safety regulations.

The key design parameters include:

- Ozone dosing rate: 6 mg/l
- Contact time: 10 minutes
- Flow rate: 1.16 m^3/s
- Contact tank volume: 1,000 m^3
- No. of contact tanks: 2.

Ozone at 6 mg/l is dosed into the MBR effluent. The design assumes that ozone has a transfer efficiency of 85% and therefore 690 kg/day is required.

5.3.2.2 Granular Activated Carbon

Gravity-fed downflow fixed bed GAC filters operating in parallel are proposed. GAC filters require daily backwash routines to maintain the filtration rate. The final product water can be used for backwashing that is accompanied by air scouring. The number of GAC filters required is dictated by Empty bed contact time (EBCT). Filters will not be available during backwashing or when they are out of service due to carbon regeneration.

The GAC filter key design parameters are listed below:

No of filters:	20
Filter size:	4 m x 6 m

- Empty bed contact time : 12 min
- GAC media depth: 1.7 m
- GAC media size: D_{10} = 1.18 mm
- Backwash rate : 30 m/h
- GAC bed expansion: 23%
- Air scour rate : 30 m/h.

5.3.2.3 Nanofiltration

An NF unit operates under pressure. NF prevents material between 1 and 10 nm from passing through the membrane. The main difference between NF and RO is that NF allows the passage of monovalent ions such as Na^+ and Cl^-. The NF process sizing was calculated by Dow Filmtec. The key design parameters include the net flux, number of membranes per module and number of modules.

- Total installed membranes surface: 237,526 m²
- Number of membranes elements: 6,392
- Number of vessels: 799 (8 elements per vessel)
- Membrane type: NF90-40034i from Dow Filmtec
- Design continuous operational net flux : 21.61 lmh
- Recovery: 70%
- Salt rejection: 85–95%
- Power: 681.17 kW
- Specific energy: 0.16 kWh/m^3

A multi-stage NF system comprising two stages proved to be the required configuration to achieve the desired process efficiencies and product water quality. With a 70% recovery and 95% salt rejection the TDS concentration is reduced from 458 to 60 mg/l. Mechanical and electrical capital costs are based on the equipment suppliers' recommendations from available raw water data. The cost estimate covers core membrane equipment; intermediate, chemical and CIP tanks; extra piping and valves; motorized equipment and pumps; additional electrical and instrumentation required to operate the system.

5.4 CAPITAL AND OPERATING COSTS ESTIMATE

The basis for the capital cost estimation was as follows:

- Rates for water reclamation plant construction were obtained from recent similar projects and were adjusted for inflation.
- Material costs for water reclamation plants were obtained from reputable suppliers. Installation costs were assumed to be a percentage of material costs.
- Unit treatment processes include all civil works, buildings, structures, mechanical equipment and piping.
- Electricity and instrumentation at a percentage (15 %) of mechanical.

- Provisional and general (P&G) costs are expressed as a percentage (25%) of the base construction and installation cost.
- Contingency was calculated at 10% of total cost.
- The rand/US dollar exchange rate was set at R10.32 and the rand/euro at R13.69, as at August 2013.

Civil, building, structural, mechanical and electrical costs were calculated using costs from previous similar projects. The costs were then adjusted for inflation. The rand/US dollar exchange rate was used for the calculation of membrane and component costs.

The following should be noted in terms of the assumptions made in the capital cost estimate:

- The MBR capital cost includes the cost of increasing the capacity of the existing anoxic, anaerobic and aerobic zones to cater for an ultimate capacity at Darvill WWW of 120 Ml/day. Cost savings will be achieved by retro-fitting the existing biological reactor with the submerged membrane modules.
- The required upgrades to the bulk electrical power supply at Darvill WWW are common to both treatment processes and have not been included.

A breakdown of the capital costs for Membrane Treatment Process A and Ozone/GAC Treatment Process B is given in Tables 5.2 and 5.3.

Table 5.2: Capital Cost Estimate for Membrane Treatment (Process A)

	Membrane Treatment Process		
Plant Size (m^3/day)	100 000		
CAPEX	**MBR**	**RO**	**UV**
Total Civils	R31 528 875	R35 622 103	R553 842
Total Mechanical	R222 459 780	R237 480 688	R13 345 601
Ancillary Equipment	R27 599 040	R49 870 944	R2 802 576
Electrical & Instrumentation	R10 650 000	R35 622 103	R2 001 840
Subtotal	**R292 237 695**	**R358 595 839**	**R18 703 860**
P&Gs (25%)	R73 059 424	R89 648 960	R4 675 965
Subtotal	**R365 297 119**	**R448 244 799**	**R23 379 825**
Contingencies (10%)	R36 529 712	R44 824 480	R2 337 982
Subtotal (excl. VAT)	**R401 826 831**	**R493 069 278**	**R25 717 807**
Grand Total (excl. VAT)	**R920 613 916**		

Table 5.3: Capital Cost Estimate for Ozone /GAC Treatment (Process B)

	Ozone / GAC Treatment Process				
Plant Size (m3/day)	100 000				
CAPEX	**MBR**	**Ozone**	**GAC**	**NF**	**UV**
Total Civils	R31 528 875	R2 134 692	R6 493 788	R35 622 103	R553 842
Total Mechanical	R222 459 780	R10 947 138	R17 053 015	R233 481 664	R13 345 601
Ancillary Equipment	R27 599 040	R2 298 899	R3 581 133	R49 031 149	R2 802 576
Electrical & Instrumentation	R10 650 000	R1 642 071	R2 557 952	R35 622 103	R2 001 840
Subtotal	**R292 237 695**	**R17 022 800**	**R29 685 888**	**R353 757 020**	**R18 703 860**
P&Gs (25%)	R73 059 424	R4 255 700	R7 421 472	R88 439 255	R4 675 965
Subtotal	**R365 297 119**	**R21 278 499**	**R37 107 361**	**R442 196 275**	**R23 379 825**
Contingencies (10%)	R36 529 712	R2 127 850	R3 710 736	R44 219 627	R2 337 982
Subtotal (excl. VAT)	**R401 826 831**	**R23 406 349**	**R40 818 097**	**R486 415 902**	**R25 717 807**
Grand Total (excl. VAT)	**R978 184 986**				

Costs for stabilization of the product water have not been included as the water will be blended at Umlaas Road Reservoir with treated water from Midmar waterworks. Therefore the cost of stabilization e.g. addition of CO_2 may be less. The calculation of the impacts on the final water chemistry of blending ratios is beyond the scope of this project.

The RO membranes reject 99.8% of salts and therefore the RO concentrate will be brackish and contain salts in the order of 3,700 mg/l. At 88% recovery from 100 Ml/day, the volume of brine produced will be 12 Ml/day. The size of the evaporation ponds required for this volume of waste was calculated as follows:

Total pond area = (Volume to evaporate) / (net evaporation rate)
= 12,000 / 0.0028
= 4,285,714, or 4,300,000 m^2 (rounded off)

This pond area could, for example, be divided into 100 ponds of 43,000 m^2 each. Provision is made for a 1 meter deep pond, or a year's storage buffer capacity, in the evaporation ponds to compensate for peak rainy seasons. Brine from RO systems is classified as "hazardous waste" according to the National Environmental Management Act (NEMA) of 1998, as mentioned in Regulation 625 of August 2012. Therefore, an evaporation pond conforming to a Class A waste disposal site (h:H) needs to be constructed for the evaporation of the brine. A budget estimate for the construction of such an evaporation pond system for Umgeni Water was obtained from Aquatan by Bigen Africa. The total construction cost of the brine evaporation ponds amounts to about R450 million.

The RO membrane process treatment train requires less capital expenditure, as would be expected because it has fewer unit processes; however, the difference in cost is not great. Given that the cost estimate accuracy is 25%, a refinement of the costs will have to be made to more accurately assess the capital cost of both projects. The operating costs should also be considered when making this assessment. An alternative treatment option would be to replace the NF membrane with a UF membrane in the ozone/GAC treatment train. This would reduce the total cost significantly while still meeting the water quality objectives, as using UF would not produce a hazardous concentrate that requires disposal. The estimated cost of a treatment train in which the NF is replaced with UF (MBR-O_3/GAC-UF-UV) is R752 million, which is approximately a R196 million saving. This process is very similar to that of the existing Goreangab Reclamation plant in Windhoek and thus has potential.to meet the design objective of producing safe potable water. It also replicates the DPR treatment train proposed by Golder & Associates (2010) for some of the eThekwini reuse projects (see annexure B-G). The only difference in the two process trains is that in the eThekwini treatment train, MBR is replaced by flocculation and clarification. The cost per megalitre for the eThekwini reuse plant is estimated as R7.6 million. The total capital cost for the 100 Ml/day Darvill reclamation plant would therefore be in the order of R761 million, which is very similar to the previous estimate.

5.5 OPERATION AND MAINTENANCE COSTS

The operation and maintenance cost estimation is derived as follows:-

- The cost of power in 2013 is 73c / kWhr

The annual operation and maintenance cost for the different processes is provided in Table 5.4 and Table 5.5.

Table 5.4: Operation and Maintenance Cost for MBR-RO-UV

Plant	**Size**	**OPEX (m^3/day)**		**Total OPEX**	
	m3/day	Fixed	Variable	Per day	Per m^3
MBR-RO-UV	100,000	R0.63	R1.86	R249,755	R2.49

The annual operating cost for 100 Ml/day production is therefore R91,160,611.

Table 5.5: Operation and Maintenance Cost for MBR-O_3/GAC-NF-UV

Plant	**Size**	**OPEX (m^3/day)**		**Total OPEX**	
	m3/day	Fixed	Variable	Per day	Per m^3
MBR-O_3/GAC-NF-UV	100,000	R0.63	R2.30	R292,790	R2.93

The annual operating cost for 100 Ml/day production is therefore R106,868,476.
The operating cost for the alternative MBR-O_3/GAC-UF-UV (Process E) would be less as the pressure to run UF membranes is less than to run NF membranes.

5.6 SUMMARY

The membrane-based process (MBR-RO-UV) would require less capital investment than the ozone /GAC (MBR-O_3/GAC-NF-UV) treatment process, based on the calculations presented. The difference in capital cost is, however, marginal at this level of accuracy. The operating cost for the membrane-based process is also marginally lower.

The cost of disposal of the brine reject from the RO and NF unit processes was not originally included in the cost calculations. This was seen as an omission by the WRC reference group and a cost estimate for brine disposal was requested.

The cost of treating the brine reject in brine evaporation ponds has been estimated at R450 million. This assumes a reject volume of 12 Ml/day based on 88% recovery and a concentrate TDS of approximately 3,700 mg/l. This cost is almost half the total project cost for each of the proposed reclamation trains. It is therefore concluded that a treatment process that avoids the inherent disposal problems and costs associated with NF and RO reject is required. A treatment train that comprises MBR-O_3/GAC-UF-UV should produce water of potable quality as this train has some similarity to the Goreangab Reclamation Plant. The Goreangab plant does not have an advanced oxidation process (UV/H_2O_2) and thus this proposed treatment train has an additional barrier. The substitution of a UF membrane for the RO and NF membrane will reduce the cost significantly. Although UF does not remove micro-organic substances there are three barriers, namely ozonation, GAC and AOP unit processes that provide this protection.

It is thus proposed that further trials be conducted to test the performance of this proposed treatment train. These trials would provide process results for the eThekwini reuse project, which has proposed a similar treatment train.

CHAPTER 6: CONCLUSION

6.1 GENERAL CONCLUSIONS

The primary objective of this investigation was to determine the efficacy of various treatment trains and individual unit processes in meeting set water quality objectives and for the removal of CECs (endocrine disruptors, pharmaceuticals, and personal care products). A group of structurally diverse target compounds was selected for evaluation based largely upon occurrences and a prioritized ranking. Several membrane types and applications were evaluated at pilot and laboratory/bench scale, including: membrane bioreactors, nanofiltration, reverse osmosis, and combinations of membranes in series. Ozonation in combination with granular activated carbon, and ultra violet radiation in combination with hydrogen peroxide (AOP) were also evaluated at bench scale. Nanofiltration and reverse osmosis were capable of significant rejection of nearly all target compounds, though compounds were detectable at trace levels in permeates. Granular activated carbon was not as effective at removing all the target compounds on its own, but in combination with ozonation it was very effective. AOP was very effective at removing steroid hormones as well as providing an additional barrier to pathogens. Findings confirm that membrane and carbon processes combined with ozonation are capable of greatly reducing the concentrations of emerging contaminants; however, some compounds are detectable in membrane permeate and carbon effluent.

All the selected treatment trains have proven to be capable of producing drinking water compliant with and exceeding local and international drinking water regulations. The decision on which is the most appropriate treatment train to be used for the Darvill reclamation design may have to be based on other factors. These will include, but not be limited to, two very important factors: namely, public health and economic cost.

The streamlined MBR-RO-UV process is more economical than the MBR-O_3/GAC-NF-UV process train and would thus be recommended of the two options. However, a serious flaw in the two processes is the cost of brine disposal using evaporation ponds; the alternative of disposing of the brine to sea is not an option inland where Darvill WWW is situated.

If reclamation is to be considered feasible at Darvill and other wastewater works in the interior, an alternative treatment train such as MBR-O_3/GAC-UF-UV will have to be considered.

6.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Operationally, by placing the NF upstream of the O_3/GAC unit, the TOC entering the O_3/GAC was reduced from an average 5.8 mg/l to less than 1 mg/l. This allowed the ozone dosage to be reduced from 9 mg/l to 6 mg/l. A further reduction in the dosage was not possible due to the difficulty of measuring the ozone dosage at lower levels. This reduction in ozone consumption would obviously have a major financial benefit at full scale. Similar operational benefits may accrue in increasing the time between carbon regeneration periods, as the substantial reduction in TOC would apply less organic load onto the carbon.

No calculation was made on the potential economic benefit derived from placing the NF upstream of the O_3/GAC. This analysis is recommended as part of future research as it was beyond the scope and time available under the current project.

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ANNEXURES

Annexure B-A

Reclamation Plant Product Water Quality Standards

New Goreangab Reclamation Plant Water Quality Standards

Physical and Organoleptic	Units	95th Percentile Limit
Calcium Carbonate Precipitation Potential	CaCO3 mg/l	4
Chemical Oxygen Demand	mg/l	Max 15; Aim for 10
Colour	mg/l Pt	10
Dissolved Organic Carbon	mg/l	Max 5; Aim for 3
Total Dissolved Solids	mg/l	1,000 max or 200 above incoming
Turbidity	NTU	Max 0.2; Aim for 0.1
UV254	abs/cm	0.065
Macro Elements		
Aluminium	Al mg/l	0.15
Ammonia	N mg/l	0.1
Chloride	Cl mg/l	250
Iron	Fe mg/l	0.05
Manganese	Mn mg/l	0.025
Nitrate and Nitrite	N mg/l	10
Nitrite	N mg/l	0.05
Sulphate	SO4 mg/l	200
Microbiological		
Heterotrophic Plate Counts	per 1 ml	100
Total Coliforms	per 100 ml	0
Faecal Coliforms	per 100 ml	0
E.coli	per 100	0

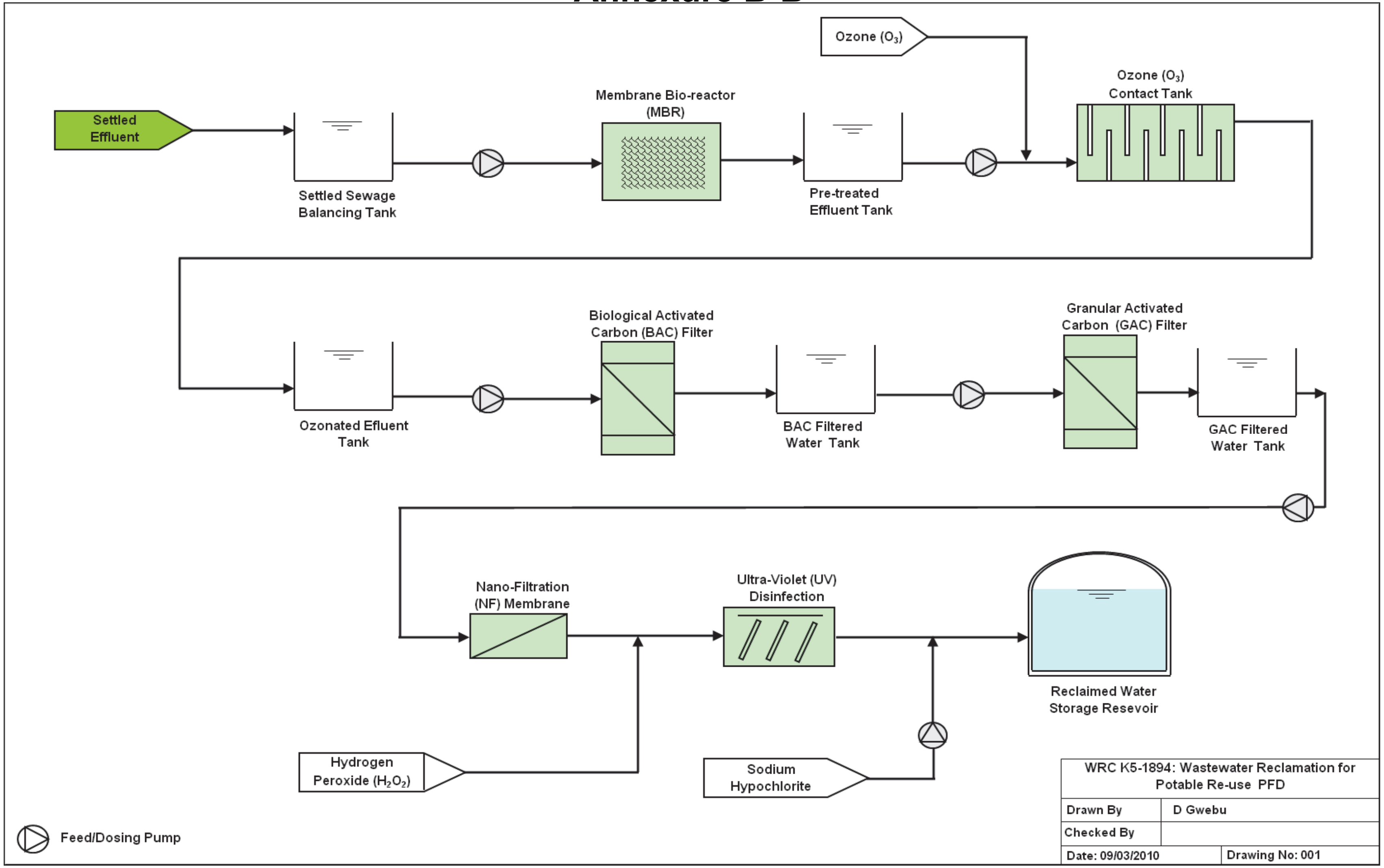
	ml	
Coliphage	per 100 ml	0
Enteric Viruses	per 10 l	0 counts per 10 l or 4 log removal
Faecal Streptococci	per 100 ml	0
Clostridium Spores	per 100 ml	0
Clostridium Viable cells	per 100 ml	0
Disinfection By-products		
Trihalomethanes	ug/l	Max 40; Aim for 20
Biological		
Chlorophyll a	ug/l	1
Giardia	per 100 l	Not more than 0 or 5 log removal
Cryptosporidium	per 100 l	Not more than 0 or 5 log removal
Note Other parameters will be adhered to, to comply with Rand Water standards * Possible stricter operational requirements for management levels		

NEWater Factory Water Quality Standards

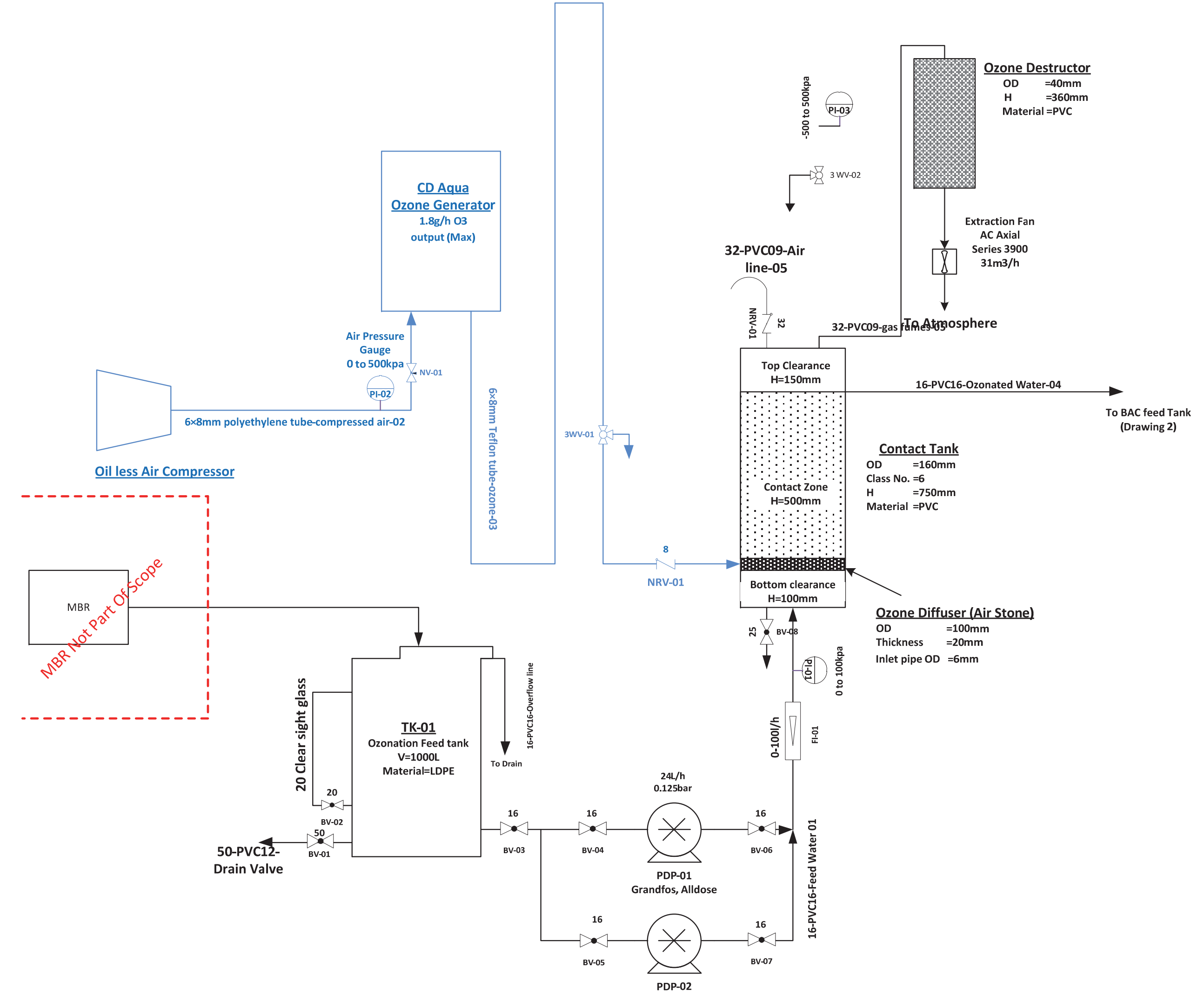
Physical and Organoleptic	Units	USEPA/WHO [2]	NEWater Factory[1]
Colour	mg/l Pt	10	<5
pH		6.5-8.5	5.2–6.2
Total Dissolved Solids	mg/l	500	22–41
Total Organic Carbon	ug/l	-	60–90
Turbidity	NTU	5	<0.1
Alkalinity	as $CaCO_3$	-	8
Conductivity	(uS/m)	-	40–71
Macro Elements			
Aluminium	Al mg/l	0.2	0.09
Ammonia	N mg/l	1.5	0.3–0.57
Chloride	Cl mg/l	250	7–11
Iron	Fe mg/l	0.3	<0.003

Manganese	Mn mg/l	0.05	<0.003
Nitrate	N mg/l	10	0.5–1.65
Nitrite	N mg/l	0.38	0.91
Sulphate	SO4 mg/l	250	0.2–0.5
Fluoride	F mg/l	1.5	0.18–0.22
Zinc	Zn mg/l	3	<0.004
Silica	As SiO_2 mg/l	-	0.2–0.3
Phosphate	As P mg/l	-	0.01–0.05
Sodium	Na mg/l	200	5–10
Microbiological			
Total Coliforms	per 100 ml	NC	<1
Faecal Coliforms	per 100 ml	ND	<1
E.Coli	per 100 ml	0	
Coliphage	per 100 ml	0	
Clostridium Perfringens	CFU per 100 ml	-	<1
Disinfection By-products			
Trihalomethanes	ug/l	Max 40; aim for 20	
Biological			
Chlorophyll a	ug/l	1	
Giardia	per 100 l	Not more than 0 or 5 log removal	
Cryptosporidium	per 100 l	Not more than 0 or 5 log removal	
Note: 1. Taken from analytical results for the months of June and July 2000. 2. Lowest limit of either the US-EPA 1998 Surface Water Regulations or WHO 1993 Guidelines for Drinking Water.			

Annexure B-B



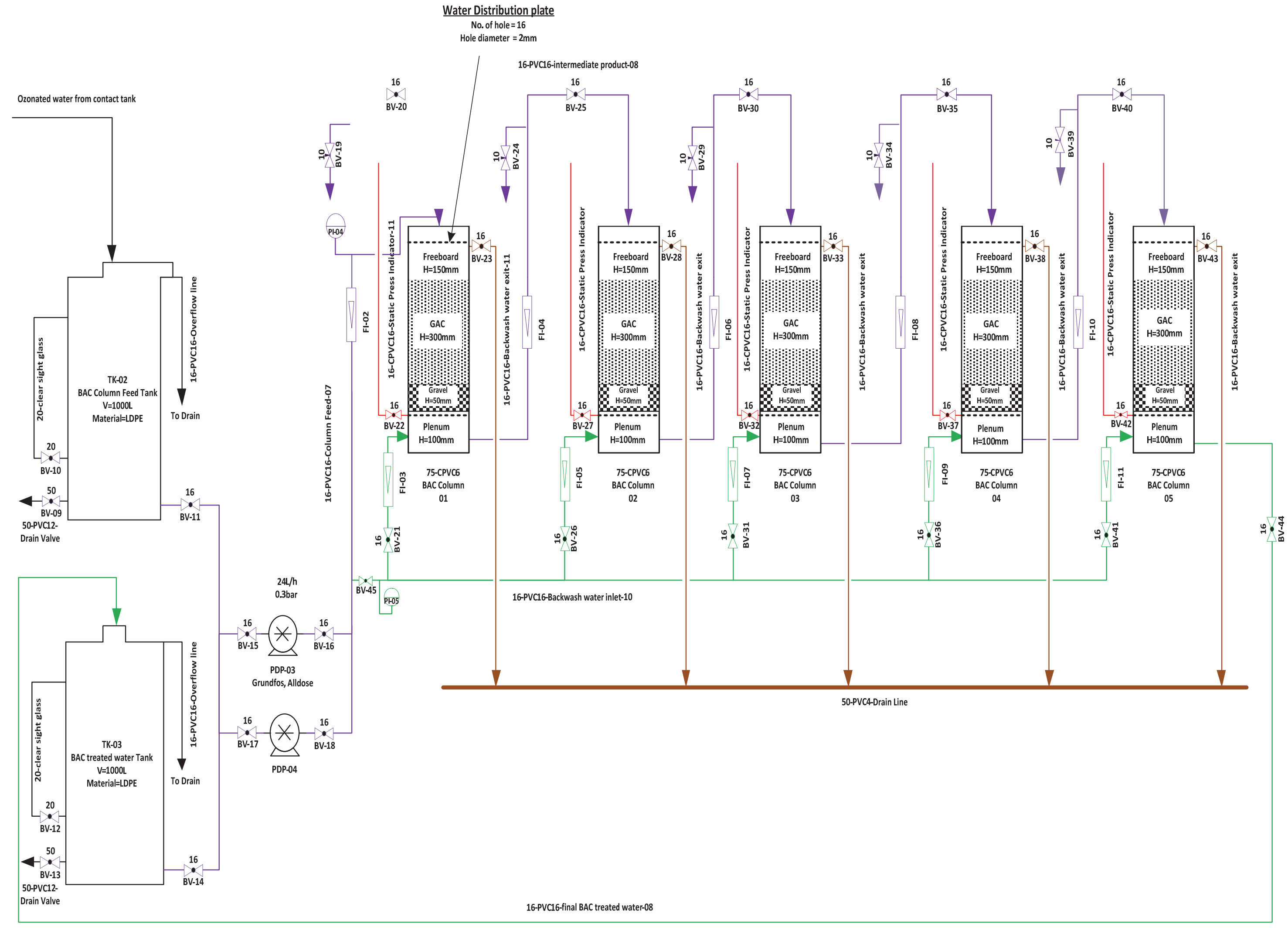
Preliminary Process Flow Diagram for Darvill Potable Water Reuse



UMGENI WATER · AMANZI *'Water for Growth and Sustainable Development'*

Project Title	Water Reclamation
Ozone Generation Plant Construction	
Drawing Title	Process & Instrumentation Diagram
Drawing Number	1
Designed By	Thulani Dlamini
Equipment List	
Displayed Text	Description
PDP	Positive Displacement Pump, Grundfos Alldose
TK	Open Tank
EF	Extraction Fan
Valve List	
BV	Ball Valve
DV	Diaphragm Valve
NRV	Non Return Valve
3 WV	3 Way Valve
Instruments List	
FI	Flow Indicator
PI	Pressure Indicator

Ozone Generation Process Flow Diagram



'Water for Growth and Sustainable Development'

Project Title	Water Reclamation
Biological Activated Carbon Pilot Plant Construction	
Drawing Title	Process & Instrumentation Diagram
Drawing Number	2
Designed By	Thulani Dlamini
Equipment List	
Displayed Text	Description
PDP	Positive Displacement Pump
TK	Storage Tank
Valve List	
BV	Ball Valve
DV	Diaphragm Valve
NRV	Non Return Valve
Instruments List	
FI	Flow Indicator
PI	Pressure Indicator
LI	Level Indicator

Granular Activated Carbon Process Flow Diagram

Annexure B-C

Ozone and GAC Operating Procedures

1 Ozone Generator Calibration and Ozone Dosage Calculation

Purpose

The purpose was to find out the ozone concentration produced by the ozone generator.

Apparatus

- Burette
- 500 ml glass conical flask
- 250 ml volumetric cylinder
- A-grade glass ware
- Spatula
- Pipette

Reagents

- Sulphuric acid conc.
- Potassium dichromate
- Potassium iodide
- Sodium thiosulphate
- Starch indicator (soluble)
- Acetic acid

Procedure

Standardisation of 0.01 N Sodium Thiosulphate

10 ml 0.01N $k_2Cr_2o_7$ was pipetted into a 250 ml conical flask. 1 ml of concentrated sulphuric acid was added. Then a spatula full of potassium iodide (KI) crystals was added and it was placed in a dark cupboard for 6 minutes. 0.01N sodium thiosulphate was titrated against the solution until a pale straw colour was visible. 2 ml of starch solution was added and the colour went blue-black. Then the sample was titrated until it was colourless. Then the volume of sodium thiosulphate used for titration was recorded.

Standardisation of Ozone Sample

3. ml of acetic acid was pipetted into a 500 ml glass conical flask, 250 ml of the ozone sample was added and immediately titrated against 0.01 N sodium thiosulphate until a pale straw colour appeared. 2 ml of starch indicator was added. The solution turned blue-black and it was titrated until it went colourless. Then the volume of sodium thiosulphate used for titration was recorded.

Ozone Demand

Power level	Flow (cc)	Time(min)	V_1(ml)	V_2(ml)	V_{ave}(ml)	Concentration	Residual (Ozonated water)
4	600	1	1.3	1.5	1.4	2.02	0
4	600	1	1.8	1.7	1.7	2.45	
4.5	600	1	3	3.1	3.05	4.4	0
4.5	600	1	3.3	3.3	3.3	4.7	
5	600	1	6.8	7	6.9	9.96	0.2
5	600	1	6.7	6.5	6.6	9.5	

mg O_3/l = (9.96 + 9.5)/2 = 9.73 mg/l

Ozone Dose

$$Ozone\ solution\ mg/l = \frac{titre(ml) \times 24000\ \ \times Na_2S_2O_3(^{mg}/_{l})}{Volume\ of\ Sample(ml)}$$

$$Ozone\ solution\ mg/l = \frac{6.8 \times 24000\ \ \times 0.00962}{100}$$

=14.44 mg/l

$$Flow\ O_3 = \frac{Concentration\ O_3\ (\frac{mg}{l})\ \times Volume\ of\ Ozonated\ Solution(l)}{Time(h)}$$

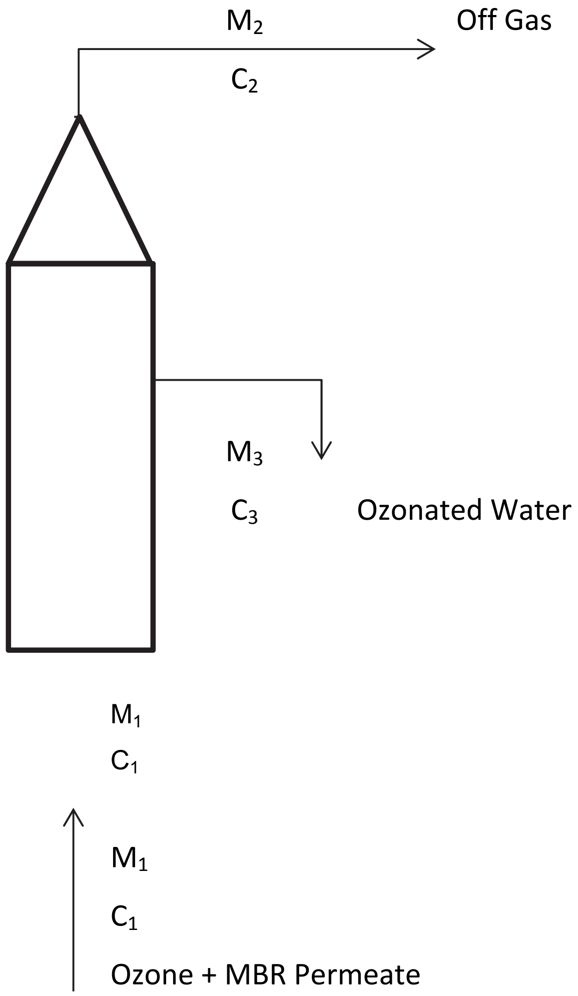
$$Flow\ O_3 = \frac{14.44\ \ \times 0.25}{\frac{1}{60}}$$

$$= 216.6\ mg/h$$

$$Dose(O_{3)} = \ \frac{216.16\ \ mg}{h} \times \frac{h}{24l\ (water)}$$

$$= 9.025\,^{mg\ O_3}/_{l\ water}$$

Mass Balance



$M_1 \ = \ mass\ flow\ rate\ of\ Ozone\ into\ the\ Contact\ tank$

$M_2 = \ Mass\ flow\ rate\ of\ off\ gas$

$M_3 = \ Mass\ flow\ of\ Ozone\ in\ water$

$Input \ = \ Output$

$Q_1C_1 = \ Q_2C_2 + \ Q_3C_3 + Ozone\ Demand$

$But\ Q_1C_1 = M_1, Q_2C_2 = \ M_2 and\ \ Q_3C_3 \ = \ M_3$

$Therefore\ M_1 = M_1 + \ \ M_3 + Ozone\ Demand$

$$Ozone\ solution\ mg/l = \frac{titre(ml) \times 24000 \ \ \times Na_2S_2O_3(^{mg}/_{l})}{Volume\ of\ Sample(ml)}$$

$$Ozone\ solution\ mg/l = \frac{6.8 \times 24000 \ \ \times 0.00883}{100}$$

= 14.44 mg/l

$$Flow\ O_3 = \frac{Concentration\ O_3\ (\frac{mg}{l})\ \times Volume\ of\ Ozonated\ Solution(l)}{Time(h)}$$

$$Flow\ O_3 = \frac{14.44\ \ \times 0.25}{\frac{1}{60}}$$

$$= 216.6\frac{mg}{h} = M_1$$

Ozone Residual Concentration

$$mg\ O_3/_l = \frac{100\ \times \Delta A}{f\ \times\ b\ \times V}$$

ΔA = Difference in absorbance between sample and blank

b = Path length of sell (cm)

V = Volume of sample (ml) (normally 90ml)

f = 0.42 (proportionality constant of indigo reagent at 600 nm compared to UV absorption of pure ozone at 258 nm)

At a flow of 36 l/h and power level 5.5, the ozone residual is as follows:

$$mg\ O_3/_l = \frac{100\ \times \Delta A}{f\ \times\ b\ \times V}$$

$$mg\ O_3/_l = \frac{100\ \times (0.153)}{0.42\ \times\ 5\ \times\ 30}$$

$$= 0.23\frac{mg}{l} = C_3$$

$$V_3 = flow\ of\ water = 24l/h$$

Off gas (Ozone Residual)

$$Ozone\ solution\ mg/l = \frac{titre(ml) \times 24000\ \ \times Na_2S_2O_3(^{mg}/_l)}{Volume\ of\ Sample(ml)}$$

$$Ozone\ solution\ mg/l = \frac{4 \times 24000\ \times 0.00962}{100}$$

= 9.2 mg/l

$$Flow\ O_3 = \frac{Concentration\ O_3\ (\frac{mg}{l})\ \times Volume\ of\ Ozonated\ Solution(l)}{Time(h)}$$

$$Flow\ O_3 = \frac{9.2\ \times 0.25}{\frac{1.5}{60}}$$

$$= 92.4\frac{mg}{h} = M_2$$

$$M_1 = Ozone\ Demand + M_2 +\ Q_3C_3$$

$$\therefore\ Ozone\ Demand = 216.6 - 92.35 - (0.23 \times 24)$$

$$= 118.73\ mg/h$$

$$= \frac{118.73\ mg/h}{24\ l/h}$$

$$= 5\ mg/l$$

4. Operational Procedure

2.1 Startup procedure

2.1.1 Ozonation Section

a) Fill MBR Permeate feed water tank.
b) Open MBR Permeate tank outlet valve (BV-03).
c) Open ozonation plant feed pump inlet and outlet valves (BV-04 and BV-05).
d) Open ozonated water outlet valve from contact tank to ozonated water tank.
e) Connect power supply for pumps and extractor fan to plug points and switch on.
f) Connect ozone generator to plug point and switch on.
g) Start the extractor fan by switching it on at the multiplug.
h) Slowly open the gas cylinder valve and use regulation valve to set outlet pressure at 50 kpa.
i) Switch on ozonation plant feed pump (PDP-01) and set flow rate to desired value.
j) Switch on ozone generator by pressing the blue button on the right hand side of the generator.
k) Open air flow by turning the black knob on the flow meter set to desired flow rate.
l) Start ozone generation by setting current on ozone generator to give desired amount of ozone.
m) Run the ozonation plant for 48 hours to fill the ozonated water tank to have enough ozonated water to run the BAC column.

2.1.1.1 GAC Section

a) Open ozonated water outlet valve (BV-11).
b) Open GAC column feed pump inlet and outlet valves (BV-15 and BV-16).
c) Open feed and product valve for each column (BV-20, BV-25, BV-30, BV35, BV40 and BV-44).
d) Start the GAC feed pump (PDP-03) to run ozonated water through GAC columns and set flow rate to 24 l/hr.
e) Monitor the feed pressure. It must not continuously increase to maximum. If that happens stop the feed pump. Check if all the columns inlet and outlet valves are opened. If there is a closed valve, first open column 1 feed sample point to release the pressure and open the closed valve.
f) Ensure that water levels in the columns are the same. Do this by opening the backwash outlet valve until the level reach the desired value. Then close the valve.
g) Ensure levels in tanks are maintained high to ensure undisturbed operation of the GAC columns.

h) Monitor the feed pressure (PI-04) and feed flow rate (FI-02, FI-04, FI-06, FI-08, and FI-10). Any reduction in flow rate to less than 20 l/h from a normal operation of 24 l/h and corresponding increase in pressure will be an indication that the filters are clogged and require backwashing.

2.1.2 Sampling procedure

Take samples for water quality monitoring. Take samples for the MBR Permeate from the MBR, Ozonated Water from the sample point on O_3 contact tank outlet (close outlet valve and open sample valve and take samples) and the O_3/GAC permeate from the GAC outlet. Take column outlet samples from sample points located at column outlets to measure quality from each GAC column. These valves must be slowly opened to take the sample without disturbing the system. Take enough samples and then close the valve. The table below shows sample to be taken, frequency of sampling and determinands.

Sample	Frequency	Determinands
MBR Permeate Ozonated Water O3/GAC Permeate	Monday – Friday	COD, Conductivity, Ammonia, Nitrates, Nitrites, Total Kjeldahl Nitrogen (TKN), Suspended Solids, Soluble reactive Phosphates (SRP), Turbidity, pH, UV_{254} absorbance
	Monday, Wednesday and Friday	Total Organic Carbon (TOC), Alkalinity, E-coli, Coliphages, Coliforms, Oil and Grease (OG), Total Dissolved solids, UV_{254} absorbance
GAC columns outlets	When required	Total Organic Carbon, UV_{254} absorbance,

2.1.3 Backwashing

Once the filters are clogged they need to be backwashed. One filter will be backwashed at a time. The backwash sequence will be as follows:

a) Close ozonated water tank outlet valve (BV-11). Disconnect the outlet pipe from the ozonated water tank and connect it to the O_3/GAC permeate tank.

b) Open O_3/GAC permeate tank outlet valve (BV-14).

c) Open GAC column feed pump inlet and outlet valves (BV-15 and BV-16).

d) Close feed inlet and outlet valves for all the columns, column BV-20, BV-25, BV-30, BV35, BV40 and BV-44.

e) Open backwash water inlet and outlet valve for the column that is backwashed. Backwash valves for the other columns must remain closed.

f) Complete GAC column backwash

g) Start backwash water pump and set flow rate to 30 l/hr.

h) Once all the columns have been backwashed disconnect the feed pipe from the GAC treated water tank, connect it back to the ozonated water tank and switch the plant back to filtration mode.

Note: the same pump will be used for feeding the columns as well as for backwash.

2.1.4 Shut down procedure

a) Turn down current on the ozone generator to zero.

b) Switch off ozone generator by pressing the blue button on the right hand side of the generator.

c) Close gas valve at the top of the gas cylinder.

d) Switch off ozonation feed pump (PDP-01).

e) Switch off GAC column feed pump (PDP-03).

f) Wait for **3 minutes** before switching off the extraction fan.

g) Switch off power supply to ozone generator on the wall plug point.

h) Switch off power supply to multiplug adapter.

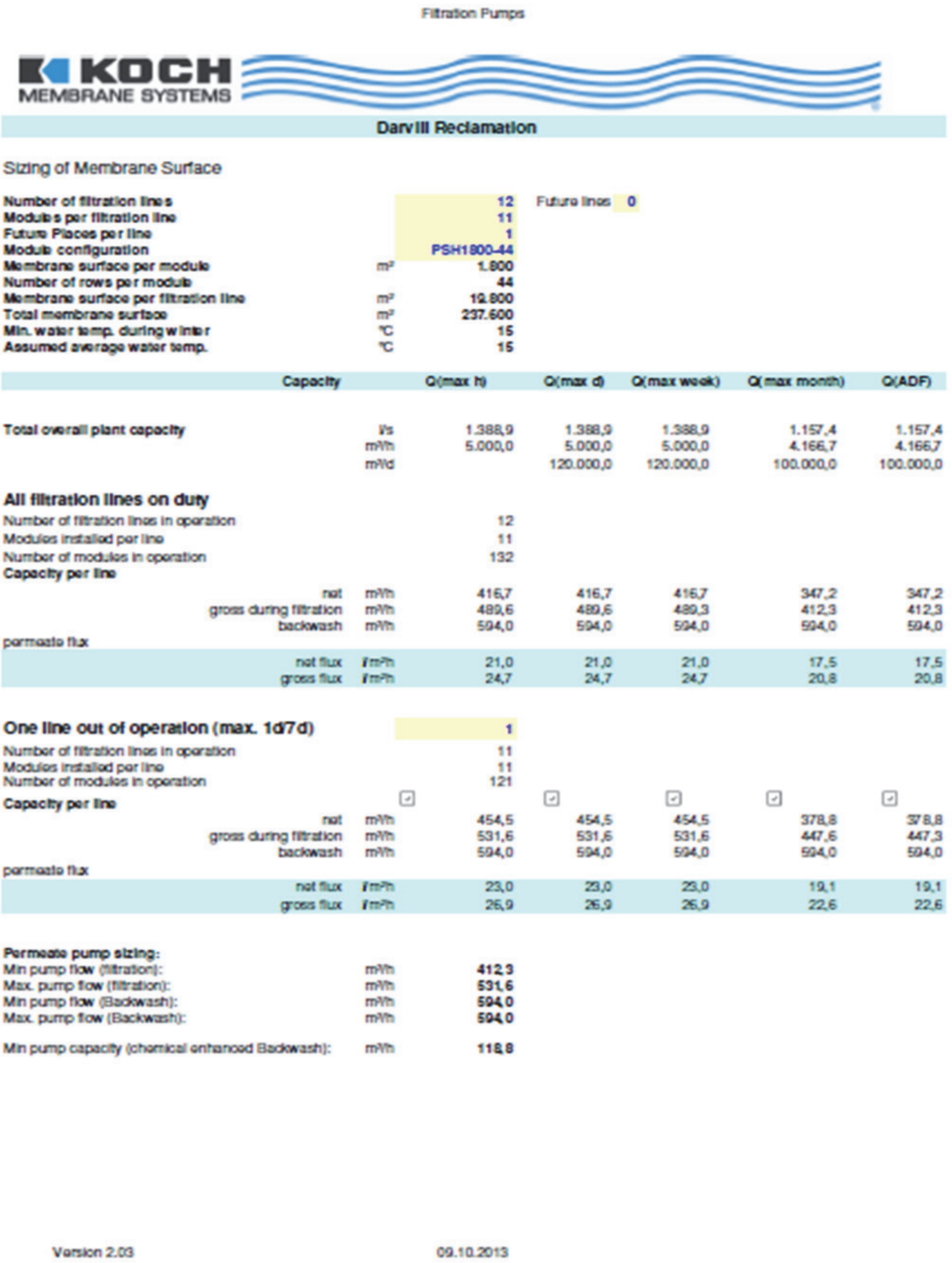
Annexure B-D

List of Analytical Laboratory Instrumentation

DETERMINAND	INSTRUMENT TYPE	MODEL NAME
NO_3 / NO_2	THERMO	AQUAKEM 600
NH_3	THERMO	AQUAKEM 600
TKN	SEAL	AUOT-ANALYSER 3
TDS	No instrument	Gravimetric Analysis
Alkalinity	METTLER	AUTOTITRATOR
SS	No instrument	Gravimetric Analysis
OG	No instrument	Gravimetric Analysis
SRP	THERMO	AQUAKEM 600
TP	THERMO	AQUAKEM 600
Turbidity	HACH	2100 AN TURBIDITIMETER
COD	NANOCOLOUR	VARIO 3_{PLUS} 500D SPECTROPHOTOMETER
BOD	YSI	5000
TOC / DOC	TEKMAR	APOLLO 9000

Annexure B-E

Koch Puron simulation for 120 Ml/day MBR Plant



Filtration Pumps

KOCH MEMBRANE SYSTEMS

Darvill Reclamation

Sizing of Membrane Surface

Number of filtration lines		12	Future lines	0
Modules per filtration line		11		
Future Places per line		1		
Module configuration		PSH1800-44		
Membrane surface per module	m^2	1.800		
Number of rows per module		44		
Membrane surface per filtration line	m^2	19.800		
Total membrane surface	m^2	237.600		
Min. water temp. during winter	°C	15		
Assumed average water temp.	°C	15		

Capacity		Q(max h)	Q(max d)	Q(max week)	Q(max month)	Q(ADF)
Total overall plant capacity	l/s	1.388,9	1.388,9	1.388,9	1.157,4	1.157,4
	m^3/h	5.000,0	5.000,0	5.000,0	4.166,7	4.166,7
	m^3/d		120.000,0	120.000,0	100.000,0	100.000,0
All filtration lines on duty						
Number of filtration lines in operation		12				
Modules installed per line		11				
Number of modules in operation		132				
Capacity per line						
net	m^3/h	416,7	416,7	416,7	347,2	347,2
gross during filtration	m^3/h	489,6	489,6	489,3	412,3	412,3
backwash	m^3/h	594,0	594,0	594,0	594,0	594,0
permeate flux						
net flux	l/m^2h	21,0	21,0	21,0	17,5	17,5
gross flux	l/m^2h	24,7	24,7	24,7	20,8	20,8
One line out of operation (max. 1d/7d)		1				
Number of filtration lines in operation		11				
Modules installed per line		11				
Number of modules in operation		121				
	☑		☑	☑	☑	☑
Capacity per line						
net	m^3/h	454,5	454,5	454,5	378,8	378,8
gross during filtration	m^3/h	531,6	531,6	531,6	447,6	447,3
backwash	m^3/h	594,0	594,0	594,0	594,0	594,0
permeate flux						
net flux	l/m^2h	23,0	23,0	23,0	19,1	19,1
gross flux	l/m^2h	26,9	26,9	26,9	22,6	22,6

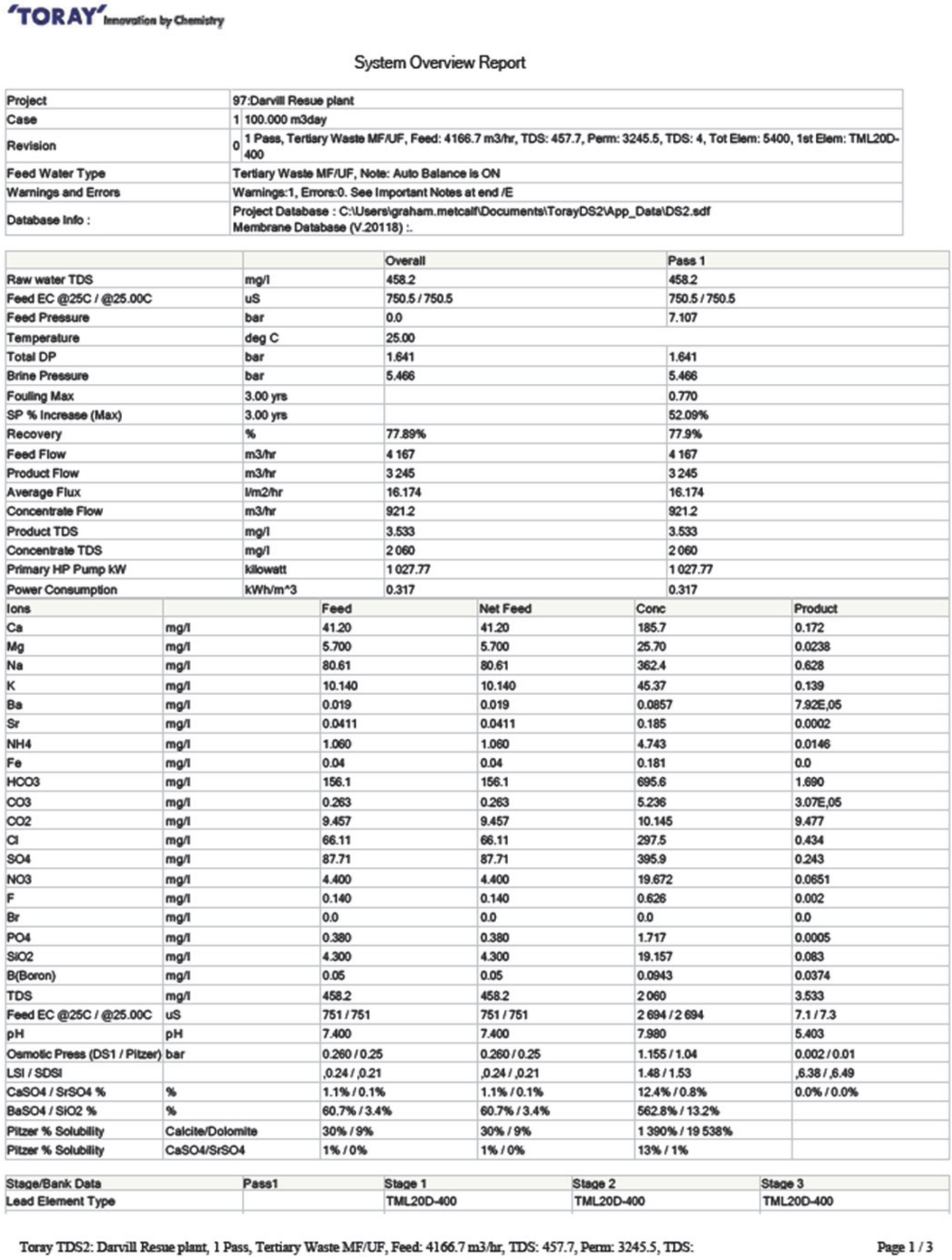
Permeate pump sizing:

Min pump flow (filtration):	m^3/h	**412,3**
Max. pump flow (filtration):	m^3/h	**531,6**
Min pump flow (Backwash):	m^3/h	**594,0**
Max. pump flow (Backwash):	m^3/h	**594,0**
Min pump capacity (chemical enhanced Backwash):	m^3/h	**118,8**

Version 2.03 09.10.2013

Annexure B-F

Toray DS2 System Overview Report for 100 Ml/day Reverse Osmosis Plant



TORAY Innovation by Chemistry

System Overview Report

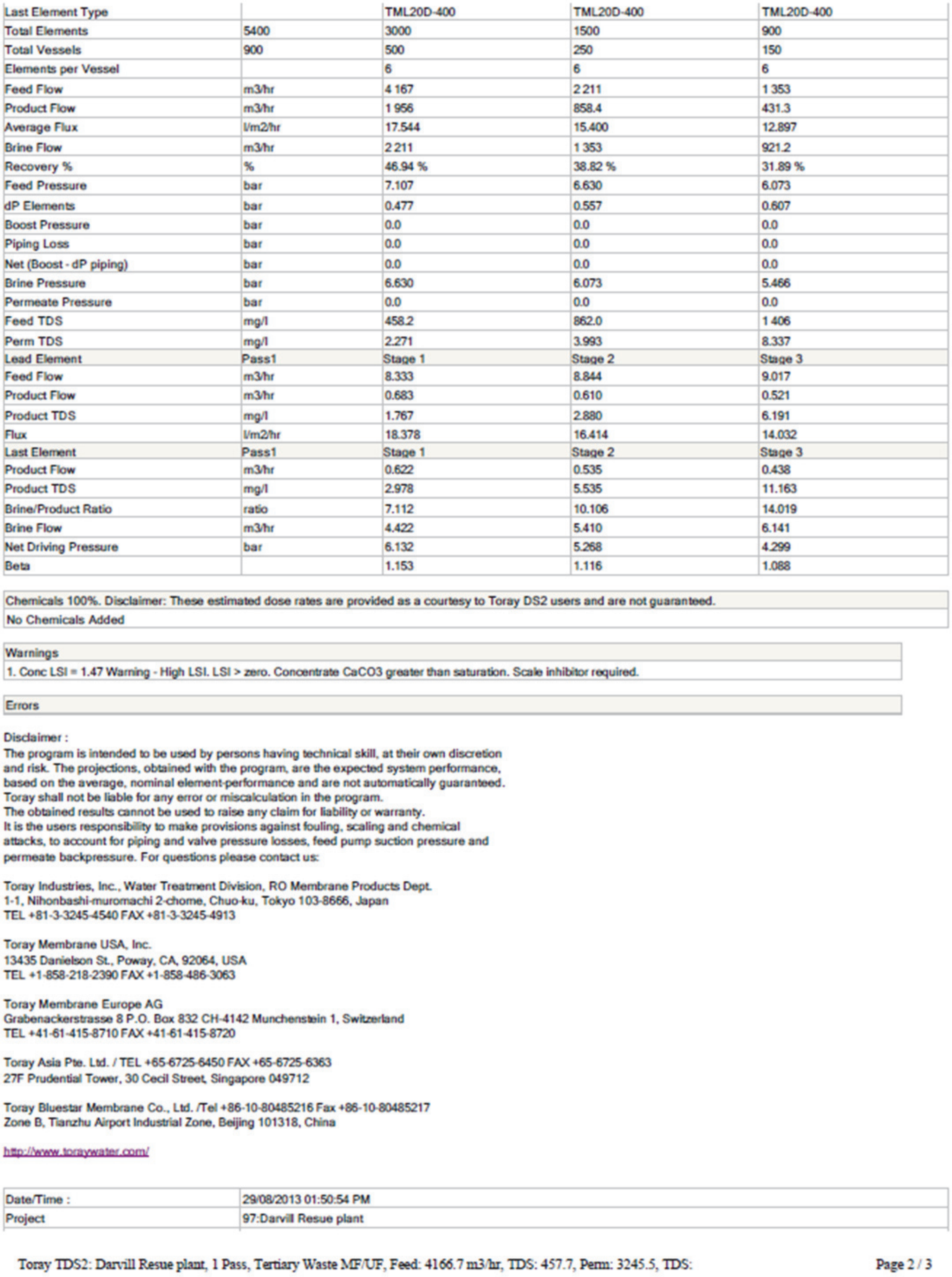
Project	97:Darvill Resue plant
Case	1 100.000 m3day
Revision	0 1 Pass, Tertiary Waste MF/UF, Feed: 4166.7 m3/hr, TDS: 457.7, Perm: 3245.5, TDS: 4, Tot Elem: 5400, 1st Elem: TML20D-400
Feed Water Type	Tertiary Waste MF/UF, Note: Auto Balance is ON
Warnings and Errors	Warnings:1, Errors:0. See Important Notes at end /E
Database Info :	Project Database : C:\Users\graham.metcalf\Documents\TorayDS2\App_Data\DS2.sdf Membrane Database (V.20118) :.

		Overall	Pass 1
Raw water TDS	mg/l	458.2	458.2
Feed EC @25C / @25.00C	uS	750.5 / 750.5	750.5 / 750.5
Feed Pressure	bar	0.0	7.107
Temperature	deg C	25.00	
Total DP	bar	1.641	1.641
Brine Pressure	bar	5.466	5.466
Fouling Max	3.00 yrs		0.770
SP % Increase (Max)	3.00 yrs		52.09%
Recovery	%	77.89%	77.9%
Feed Flow	m3/hr	4 167	4 167
Product Flow	m3/hr	3 245	3 245
Average Flux	l/m2/hr	16.174	16.174
Concentrate Flow	m3/hr	921.2	921.2
Product TDS	mg/l	3.533	3.533
Concentrate TDS	mg/l	2 060	2 060
Primary HP Pump kW	kilowatt	1 027.77	1 027.77
Power Consumption	kWh/m^3	0.317	0.317

Ions		Feed	Net Feed	Conc	Product
Ca	mg/l	41.20	41.20	185.7	0.172
Mg	mg/l	5.700	5.700	25.70	0.0238
Na	mg/l	80.61	80.61	362.4	0.628
K	mg/l	10.140	10.140	45.37	0.139
Ba	mg/l	0.019	0.019	0.0857	7.92E,05
Sr	mg/l	0.0411	0.0411	0.185	0.0002
NH4	mg/l	1.060	1.060	4.743	0.0146
Fe	mg/l	0.04	0.04	0.181	0.0
HCO3	mg/l	156.1	156.1	695.6	1.690
CO3	mg/l	0.263	0.263	5.236	3.07E,05
CO2	mg/l	9.457	9.457	10.145	9.477
Cl	mg/l	66.11	66.11	297.5	0.434
SO4	mg/l	87.71	87.71	395.9	0.243
NO3	mg/l	4.400	4.400	19.672	0.0651
F	mg/l	0.140	0.140	0.626	0.002
Br	mg/l	0.0	0.0	0.0	0.0
PO4	mg/l	0.380	0.380	1.717	0.0005
SiO2	mg/l	4.300	4.300	19.157	0.083
B(Boron)	mg/l	0.05	0.05	0.0943	0.0374
TDS	mg/l	458.2	458.2	2 060	3.533
Feed EC @25C / @25.00C	uS	751 / 751	751 / 751	2 694 / 2 694	7.1 / 7.3
pH	pH	7.400	7.400	7.980	5.403
Osmotic Press (DS1 / Pitzer)	bar	0.260 / 0.25	0.260 / 0.25	1.155 / 1.04	0.002 / 0.01
LSI / SDSI		,0.24 / ,0.21	,0.24 / ,0.21	1.48 / 1.53	,6.38 / ,6.49
CaSO4 / SrSO4 %	%	1.1% / 0.1%	1.1% / 0.1%	12.4% / 0.8%	0.0% / 0.0%
BaSO4 / SiO2 %	%	60.7% / 3.4%	60.7% / 3.4%	562.8% / 13.2%	
Pitzer % Solubility	Calcite/Dolomite	30% / 9%	30% / 9%	1 390% / 19 538%	
Pitzer % Solubility	CaSO4/SrSO4	1% / 0%	1% / 0%	13% / 1%	

Stage/Bank Data	Pass1	Stage 1	Stage 2	Stage 3
Lead Element Type		TML20D-400	TML20D-400	TML20D-400

Toray TDS2: Darvill Resue plant, 1 Pass, Tertiary Waste MF/UF, Feed: 4166.7 m3/hr, TDS: 457.7, Perm: 3245.5, TDS: Page 1 / 3



Last Element Type		TML20D-400	TML20D-400	TML20D-400
Total Elements	5400	3000	1500	900
Total Vessels	900	500	250	150
Elements per Vessel		6	6	6
Feed Flow	m3/hr	4 167	2 211	1 353
Product Flow	m3/hr	1 956	858.4	431.3
Average Flux	l/m2/hr	17.544	15.400	12.897
Brine Flow	m3/hr	2 211	1 353	921.2
Recovery %	%	46.94 %	38.82 %	31.89 %
Feed Pressure	bar	7.107	6.630	6.073
dP Elements	bar	0.477	0.557	0.607
Boost Pressure	bar	0.0	0.0	0.0
Piping Loss	bar	0.0	0.0	0.0
Net (Boost - dP piping)	bar	0.0	0.0	0.0
Brine Pressure	bar	6.630	6.073	5.466
Permeate Pressure	bar	0.0	0.0	0.0
Feed TDS	mg/l	458.2	862.0	1 406
Perm TDS	mg/l	2.271	3.993	8.337
Lead Element	Pass1	Stage 1	Stage 2	Stage 3
Feed Flow	m3/hr	8.333	8.844	9.017
Product Flow	m3/hr	0.683	0.610	0.521
Product TDS	mg/l	1.767	2.880	6.191
Flux	l/m2/hr	18.378	16.414	14.032
Last Element	Pass1	Stage 1	Stage 2	Stage 3
Product Flow	m3/hr	0.622	0.535	0.438
Product TDS	mg/l	2.978	5.535	11.163
Brine/Product Ratio	ratio	7.112	10.106	14.019
Brine Flow	m3/hr	4.422	5.410	6.141
Net Driving Pressure	bar	6.132	5.268	4.299
Beta		1.153	1.116	1.088

Chemicals 100%. Disclaimer: These estimated dose rates are provided as a courtesy to Toray DS2 users and are not guaranteed.
No Chemicals Added

Warnings
1. Conc LSI = 1.47 Warning - High LSI. LSI > zero. Concentrate CaCO3 greater than saturation. Scale inhibitor required.

Errors

Disclaimer :
The program is intended to be used by persons having technical skill, at their own discretion
and risk. The projections, obtained with the program, are the expected system performance,
based on the average, nominal element-performance and are not automatically guaranteed.
Toray shall not be liable for any error or miscalculation in the program.
The obtained results cannot be used to raise any claim for liability or warranty.
It is the users responsibility to make provisions against fouling, scaling and chemical
attacks, to account for piping and valve pressure losses, feed pump suction pressure and
permeate backpressure. For questions please contact us:

Toray Industries, Inc., Water Treatment Division, RO Membrane Products Dept.
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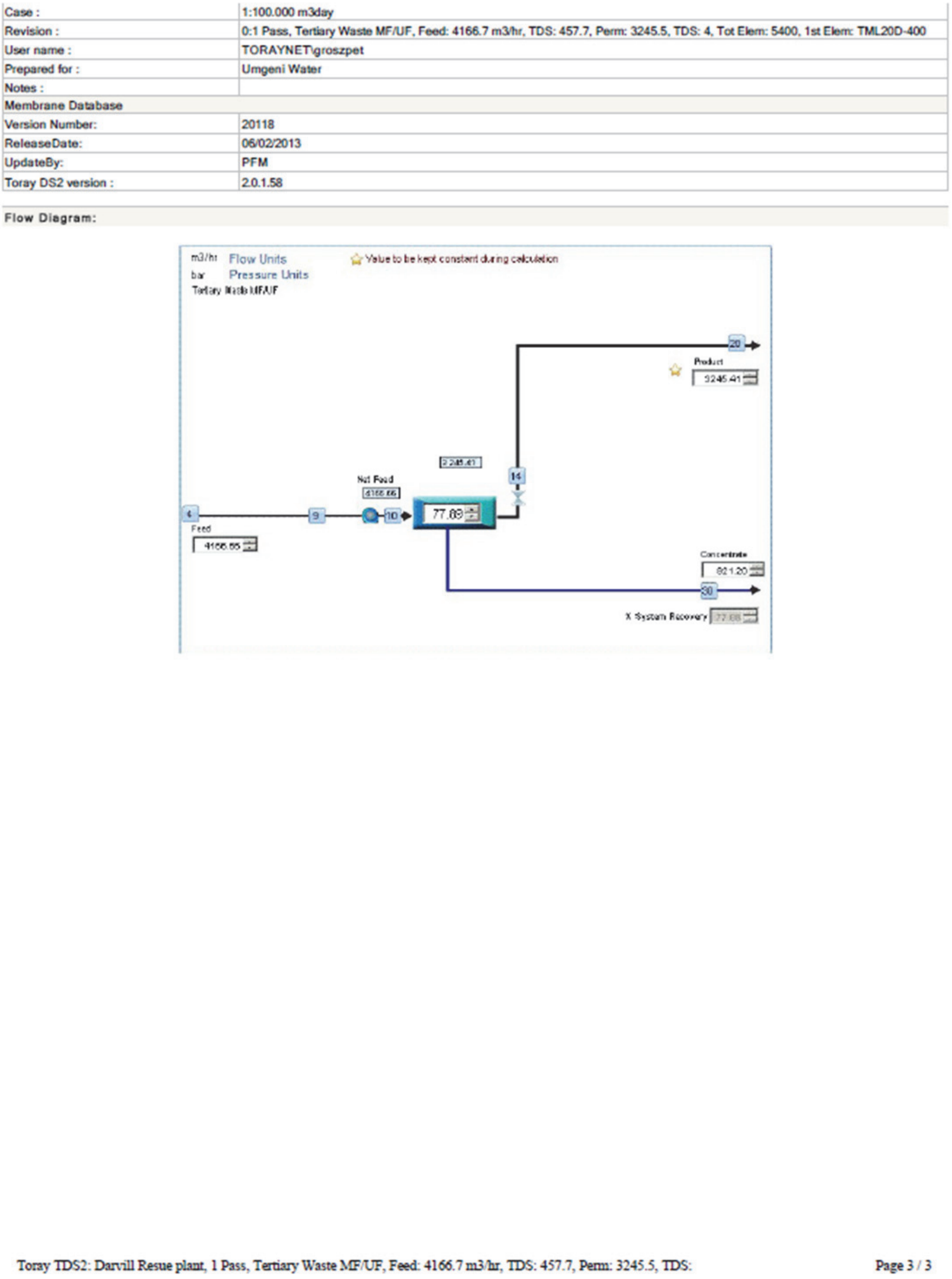
Toray Bluestar Membrane Co., Ltd. /Tel +86-10-80485216 Fax +86-10-80485217
Zone B, Tianzhu Airport Industrial Zone, Beijing 101318, China

http://www.toraywater.com/

Date/Time :	29/08/2013 01:50:54 PM
Project	97:Darvill Resue plant

Toray TDS2: Darvill Resue plant, 1 Pass, Tertiary Waste MF/UF, Feed: 4166.7 m3/hr, TDS: 457.7, Perm: 3245.5, TDS: Page 2 / 3



Case :	1:100.000 m3day
Revision :	0:1 Pass, Tertiary Waste MF/UF, Feed: 4166.7 m3/hr, TDS: 457.7, Perm: 3245.5, TDS: 4, Tot Elem: 5400, 1st Elem: TML20D-400
User name :	TORAYNET\groszpet
Prepared for :	Umgeni Water
Notes :	
Membrane Database	
Version Number:	20118
ReleaseDate:	06/02/2013
UpdateBy:	PFM
Toray DS2 version :	2.0.1.58

Flow Diagram:

Toray TDS2: Darvill Resue plant, 1 Pass, Tertiary Waste MF/UF, Feed: 4166.7 m3/hr, TDS: 457.7, Perm: 3245.5, TDS:

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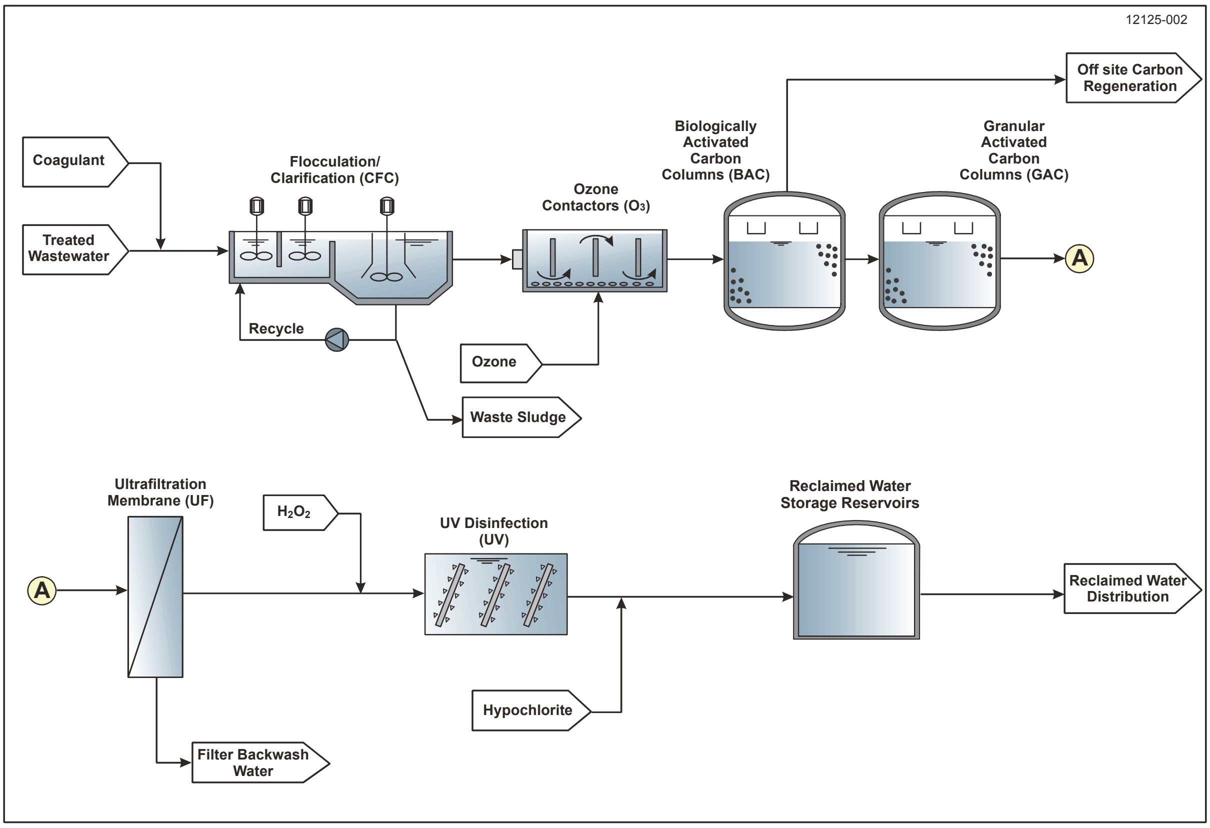
Annexure B-G

Direct Potable Reuse Option for eThekwini Municipality



*Golder & Associates (2010) Feasibility Study of Project Options for Reclamation and Reuse of Treated Sewage Effluents