A COMPARATIVE EVALUATION OF MEMBRANE BIOREACTOR TECHNOLOGY AT DARVILL WASTEWATER WORKS

by

Graham James Metcalf

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Supervisor

Professor Lingam Pillay

Co-Supervisor/s

Dr Lidia Auret

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“**DECLARATION**

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ABSTRACT

Water scarcity is one of the overriding concerns of the 21st century. Improving wastewater treatment is a relatively cost-effective solution that reduces strain on the available water supply. Reducing and improving the quality of wastewater discharges should be at the forefront of integrated water management.

The aim of the research was to investigate the ability of different Membrane Bioreactor (MBR) configurations to treat municipal wastewater to a standard above that achieved by conventional processes. The research objective was to install two MBR pilot plants with different configurations to run parallel (using the same influent wastewater) to the Darvill Wastewater Works (WWW). The performance of the two MBR pilot plants and the Darvill WWW is compared in terms of their treatment efficacy and performance reliability.

A number of MBR comparative studies have been undertaken internationally, but none in South Africa. The two MBRs tested (Toray and Norit) have previously been pilot tested on municipal sewage by other researchers and therefore the results from these studies have proved useful for comparing performance.

The MBR pilot plants were operated for an extended period of one year in order to take into account seasonality and variability of influent quality. Samples of influent and effluent were taken and analysed on a daily basis. The Darvill WWW is currently operational so these samples were already taken on a routine basis. The performance of the MBR pilot plants and Darvill WWW were compared by analysing the effluent water quality data using statistical techniques (t-test and F-test). A reliability analysis was also undertaken to determine performance against set water quality discharge standards.

Based on the operating experience at Darvill and recorded MBR performance the average flux for the submerged Toray MBR system was 17 lmh, whereas that for the sidestream Norit MBR system was 37.5 lmh. The predicted peak flux for the Toray membrane was 20 lmh whereas for the Norit sidestream membrane it was 45 lmh. The predicted cleaning frequency for the Toray MBR is 5-6 weeks and 7-8 weeks for the Norit MBR.

The MBR pilot plants out-perform the conventional activated sludge and secondary clarification process that is operated at the Darvill WWW for all determinands measured with the exception of phosphate removal. The performance of the MBRs could not be separated in terms of treatment efficacy with regard to all determinands as both outperformed the other depending on the determinand measured.

The results showed that MBRs produce an effluent water quality that exceeds the capability of the conventional activated sludge process (CASP) operated at the Darvill WWW. The reliability of the MBR pilot plants was also higher than that of the Darvill WWW. MBRs thus have an advantage if compliance with stricter discharge standards is required or if treatment of the effluent for reclamation is the goal.

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ACRONYMS AND ABBREVIATIONS

AOP	Advanced Oxidation Process
ASTs	Activated Sludge Tanks
BAC	Biological Activated Carbon
BOD	Biochemical Oxygen Demand
CAS	Conventional Activated Sludge
CFU	Colony Forming Unit
CIP	Cleaning in Place
COD	Chemical Oxygen Demand
DAF	Dissolved Air Flotation
DBP	Disinfection By-products
d.f	Degrees of freedom
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
F:M Ratio	Food to Mass Ratio
FS	Flat Sheet
GAC	Granular Activated Carbon
H_2O_2	Hydrogen Peroxide
HF	Hollow Fibre
HRT	Hydraulic Retention Time
IPR	Indirect Potable Reuse
LRV	Log Removal Value
MBR	Membrane Bioreactor
MF	Microfiltration
MLSS	Mixed Liquor Suspended Solids
MWCO	Molecular Weight Cut-off
NH_3	Ammonia
NO_3	Nitrate
NTU	Nephelometric Turbidity Units
OG	Oil and Grease
O&M	Operation and Maintenance
PFU	Plaque Forming Units
PLC	Programmable Logic Control
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
SRP	Soluble Reactive Phosphate
SRT	Solids Retention Time

TDS	Total Dissolved Solids
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
WWW	Wastewater Works

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

1.1.1 Water Scarcity

Water scarcity is one of the overriding concerns of the 21st century. The world is changing in ways that will both exacerbate water scarcity and threaten the quality of the current water supply (Barbour et al., 2009). As populations grow and consumer demand patterns increase with development and industrialization, the pressure on available water resources increases. Water is a finite resource and thus scarcity is inevitable unless demand is managed or alternatives, such as desalination, are used to augment supply. Desalination, however, has its own challenges, especially when considering the environmental impacts and cost profile. The benefit is also largely limited to coastal areas. Utilizing the remaining untapped resources generally comes at a great economic cost, as the more economical resources have already been developed. Not only are water resources limited, but they are also being polluted making available resources unfit for use without costly treatment. This dual scenario of insufficient supply `and polluted resources is a universal problem and South Africa is similarly afflicted.

The United Nations (UN) classifies an area as water stressed when annual water supplies drop below 1700 m^3 per person. When annual water supplies drop below 1000 m^3 per person, the population faces water scarcity. South Africa falls in the latter category (WWAP, 2012). South Africa has many large scale surface water impoundments and transfer schemes, and government institutions continue to plan and implement new schemes to meet future demands. Supply-side measures are reported (WRC, 2016) to increase water supply by 16% to 17.8 km^3 by 2035. The forecasted demand, based on current water use patterns and the government’s national development plan, is estimated as 18.9 km^3. This is a deficit of 6.1% and therefore there needs to be a marked change in the country’s use and management of water resources. Wastewater treatment is a relatively cost-effective solution that reduces the strain on the available water supply in a number of ways. Treating wastewater effectively protects downstream resources from pollution, and by reusing wastewater, demand on existing supplies can be reduced. Improving efficiencies in the use of wastewater should, therefore, be at the forefront of this management change.

Wastewater is a neglected resource and innovation in its use will assist in diversifying the country's water resources portfolio and making future water use more sustainable. Recycling and reclamation are paramount to achieving the maximum benefit from wastewater, but managing the quality of wastewater is equally important. Wastewater effluent not compliant with discharge standards pollutes the environment and has wide ranging negative impacts. Aquatic ecological environments suffer, the risk of water borne diseases increases, and the cost of downstream treatment increases as pollution of water resources takes place.

1.1.2 Wastewater Management and Treatment

Wastewater management has not received as much attention as potable water supply in South Africa. There are a number of reasons for this, but a major factor has been the focus in the last two decades on addressing the imbalances of the past. Potable water provision to unserved communities has thus been a priority for the government. The appropriate and effective treatment of wastewater has often been sidelined or even ignored. This has resulted in the discharges from wastewater works (WWW) being non-compliant and being a pollution source to the environment. This is evidenced by the poor Green Drop performance where only 50 of South Africa's more than 1000 odd wastewater works had received Green Drop accreditation (Macleod, 2016). Green Drop, as it is commonly known, is a strategy for incentive-based regulation of wastewater works implemented by the Department of Water Affairs and Sanitation (DWS). The continued lack of investment in sanitation (wastewater) is clear when viewing recent Municipal Water Infrastructure Grant (MWIG) allocations. Investment in sanitation per municipality makes up only 5-15% of the total water and sanitation budget in KwaZulu-Natal (Umgeni Water, 2013). This under allocation of funds is mirrored at the national level where in 2015, approximately R12 billion was allocated for water infrastructure development and R1.5 billion for sanitation services. This equates to 76% and 9% of the total DWS budget respectively (DWS, 2015).

Investing in sanitation projects and improving the treatment of wastewater within the country is a serious issue that needs to be addressed. Effective treatment of wastewater is a complex issue as it depends on a number of factors, including the influent water quality, volume, intended use and the treatment technology choice.

1.1.2.1 Treatment technologies

Advanced treatment technologies can treat wastewater to such a high standard that it is safe for use as drinking water. These technologies are, however, costly and are not appropriate for the majority of WWW that discharge their effluent into the environment. The choice of treatment technology must be appropriate for the intended use. There are many instances where conventional and simple technologies are applicable for the design of a WWW, for example; oxidation ponds. Small WWW are ubiquitous in South Africa and simple treatment processes that can be managed within the limitations and resources of the responsible water authorities and individuals are required.

Positioned somewhere in-between advanced treatment and primary treatment, there are treatment technologies that offer the possibility of improved effluent quality performance beyond that which can be achieved by conventional wastewater treatment. Globally, effluent discharge standards are becoming more onerous. Increasingly stringent regulations require that the effluent from WWW consistently meets a certain standard and thus the reliability and performance of the chosen treatment process is paramount. Newer technologies, such as Membrane Bioreactors (MBRs), claim to have a number of advantages over conventional treatment, specifically with respect to effluent water quality (Sutherland, 2010). Conventional treatment, while effective, can experience problems resulting in poor effluent water quality.

1.1.2.2 Membrane bioreactors (MBR)

A decade ago, Membrane Bioreactors (MBRs) represented a relatively new technology that was increasingly being used throughout the world to treat domestic sewage at municipal wastewater works (Le Clech et al., 2003). Nowadays they are increasingly being recognized as the process treatment of choice for the treatment of high-strength wastewater, containing complex and recalcitrant compounds (Bilad et al., 2011). Although there are many examples of the use of MBRs internationally, their use in South Africa is still very limited. MBRs offer a number of advantages over conventional treatment technologies that make them attractive as a treatment technology choice. These include improved effluent water quality and the ability to treat high organic loads. A MBR makes use of a micro-filtration (MF) or ultra-filtration (UF) membrane to remove solids from wastewater and combines this with a traditional activated sludge process for biological treatment. The membrane replaces the clarification (phase separation) step in conventional treatment. Because the membrane is a physical barrier, almost 100% of solids can be removed. The ability of different filtration systems to remove contaminants from water is illustrated in **Figure 1** below. An added advantage of MBRs is that depending on the type of membrane used (MF or UF) pathogens and viruses can also be removed, making the effluent safer. Prior to entering the membrane tank, biological nutrient removal (BNR) takes place in an aeration tank. Depending on the application, this step can include anaerobic and anoxic tanks. MBRs can also be retrofitted to existing aeration tanks, increasing the plants overall capacity and thus reducing capital expenditure.

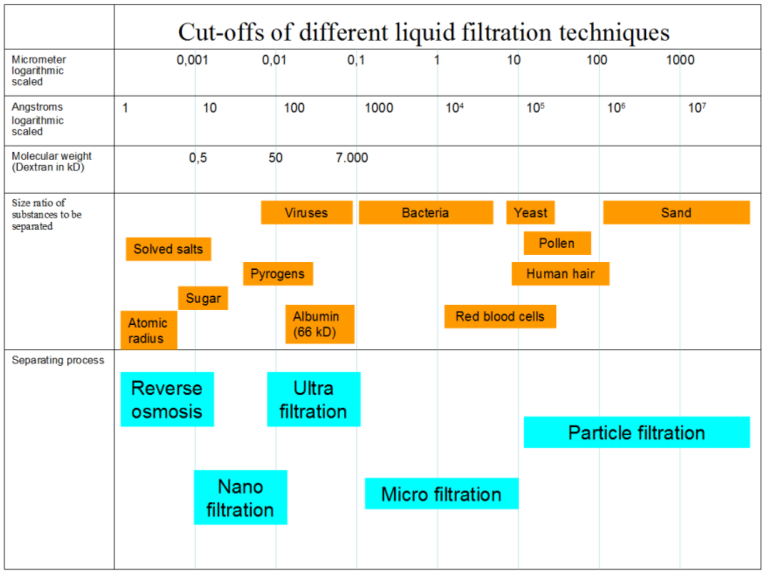

Figure 1: Cut-offs of different liquid filtration techniques

Membranes are being used in varying applications across different industries. They are frequently used in the food and beverage, dairy, pharmaceutical, metallurgy, textile, pulp and paper and chemical industries (Mulder, 1996). For a number of decades they have been used extensively in water treatment, and even more in desalination. In wastewater treatment, they are commonly used to treat a variety of waste streams from industry. Membranes offer advantages over other treatments options, that have seen them widely adopted.

1.1.3 Problem Identification

1.1.3.1 Umgeni Water Darvill wastewater works

Umgeni Water is a regional water utility responsible for both bulk water and wastewater treatment within its operational area. The Darvill WWW, situated in Pietermaritzburg, is Umgeni Water’s largest wastewater works with a design capacity of 65 Mℓ/day. The average daily flow of the Darvill WWW in 2011 was 70 Mℓ/d and therefore the works was operating over-capacity. In addition to the increase in the hydraulic load with development in Pietermaritzburg, a 33% increase in the organic load has been observed since 2008.

The increase in the organic load has put a strain on the capacity of the plant to biologically treat and remove nutrients, especially nitrogen in the form of ammonia, from the wastewater. A number of the unit processes are currently operating well above nominal capacity, with the key limiting factor being the aeration capacity, leading to the discharge of non-compliant effluent into the Msunduzi River at times, especially in winter when biological processing is slower. Related sludge age issues, sludge bulking and sludge carry over problems are also increasing significantly.

The WWW needs to be upgraded and Umgeni Water is interested in the possible benefits of utilizing MBR technology as a treatment option for Darvill WWW.

1.1.3.2 MBR pilot plant trials

As a result of these operational constraints, MBR technology was proposed as a possible solution. Two of the most important perceived benefits were MBRs reported ability to cope with high organic loads, and to produce excellent effluent water quality (Mack et al., 2004; Huang et al., 2010 and Bornare et al., 2014). Additionally, an economic saving could have possibly been achieved in that the MBR membrane modules could be retrofitted into the existing activated sludge tanks, reducing the size of the required upgrade.

Increases in water demand have placed Umgeni Water's water resources under strain and while the situation is not yet dire, the possibility of drought and water shortages is of concern. A diversification of Umgeni Water's water resources portfolio would potentially increase available resources and reduce risk. This is eminently true of wastewater reclamation, which is not impacted upon by drought to the same extent as other water resources. MBRs are promoted in the literature as an ideal pre-treatment for advanced treatment technologies used in reclamation schemes. The utilization of MBRs at Darvill would make the option of implementing reuse in the future more feasible.

As Umgeni Water was not familiar with the technology, it was deemed appropriate to test the technology before committing to any decision. A number of different MBR technologies were identified in the market, but only three were available for participation in the MBR trials to be conducted on site at Darvill WWW. Since MBR performance is highly dependent on feedwater quality, a true comparison of the performance of different MBR technologies can only be achieved when they are tested against the same feedwater matrix (Judd, 2011). The research, therefore, undertakes the simultaneous trialling of the MBR technologies challenged with the same feedwater. The analysis and testing of the performance of these MBR technologies, at a pilot scale, is presented in this thesis.

1.2 AIMS AND OBJECTIVES

1.2.1 Aim

The aim of the research investigation was to research and assess the ability of different MBR configurations to treat municipal wastewater with an industrial component to a standard above that achieved by conventional process technologies and to meet or exceed the regulated effluent water quality discharge requirements.

1.2.2 Objectives

The main objectives of this research were:

(1) To compare the relative performance of two MBR configurations operated in parallel to the Darvill WWW in terms of the following:

- a) Permeate flux (sustainable flux rate);
- b) Maintenance requirements (backwash/relaxation frequency, cleaning in place (CIP));
- c) Quantification of the treatment efficacy by measuring the removal efficiencies of specific pollutants.

(2) To compare the relative performance of the MBR pilot plants with the conventional treatment process used at Darvill WWW in terms of effluent quality and process reliability;

(3) Establish the peak sustainable flux rates of the membranes;

(4) Provide high level cost estimation for the integration of MBR at Darvill WWW.

1.3 SCOPE

In order to generate representative performance data and demonstrate the performance as close to full-scale conditions as possible, the relative performance of the MBR technologies was evaluated through the installation of two MBR pilot plants at the Darvill Wastewater Works. The pilot plants were installed on-site and were operated in parallel utilizing the same feedwater as the main plant. The performance of the MBRs could thus be directly compared to the performance of the full-scale plant. The plants were operated for a minimum of seven months in order to take into account seasonal variations in feedwater quality and operating conditions.

To compare the relative performance of the two MBR pilot systems (technologies), the following criteria were used for evaluation:

- Operating parameters with respect to:
  - Permeate flux (sustainable flux rate),
  - Operating pressures,
  - Maintenance requirements (backwash/relaxation frequency, cleaning in place (CIP)),
  - Assessment of the fouling trend of the membranes at peak flows.
- The stability of operation from a process perspective and how each system responds to up-set conditions;
- An assessment of the permeate water quality produced in relation to defined water quality performance standards;
- An assessment of individual process reliability of MBRs, compared to Darvill WWW.

1.4 THESIS STRUCTURE

The following chapter (**Chapter 2**) contains information on the fundamentals of MBRs. These are looked at from a design and operating perspective and how external and internal factors, such as feedwater quality, solids retention time (SRT), food to micro-organism ratio (F:M), flux rate, fouling and cleaning in place, impact on the performance of a MBR.

Chapter 3 is a literature review and gives a brief summary of MBRs use internationally and in South Africa. The benefits and limitations of pilot testing are discussed from a research perspective. Case studies are presented outlining the performance of MBR technology in various applications, some of which use the same MBR technology adopted in this study, affording direct comparison of performance.

Chapter 4 is an extension of the literature review and introduces the project design protocol that was employed to perform this research. It explains the processes required for the acquisition, construction and installation of the pilot plants, as well as the methods used for experimental data acquisition and processing. It also discusses the statistical methods used to compare the relative performance of the pilot plants and the Darvill WWW.

Chapter 5 compares the pilot plant performance using the MBR permeate water quality results and Darvill WWW final effluent results. The results are presented graphically and as summarized statistical results. The student t-test and F-test were used to compare the means and variances of the effluent from the different plants and a reliability analysis was undertaken.

In **Chapter 6,** the results of the MBR peak tests are presented. The peak tests were conducted to determine the membranes peak flux capability.

Lastly, in **Chapter 7**, the major findings of the research are presented and conclusions are drawn.

CHAPTER 2: LITERATURE REVIEW MBR FUNDAMENTALS

2. MBR FUNDAMENTALS

2.1 MBR Configurations

The MBR process is a suspended growth activated sludge system that uses microporous membranes for solid/liquid separation in lieu of secondary clarifiers. The typical arrangement, shown in **Figure 2,** includes submerged membranes in the aerated portion of the bioreactor, an anoxic zone and internal mixed liquor recycle (e.g. Modified Ludzack-Ettinger (MLE) configuration).

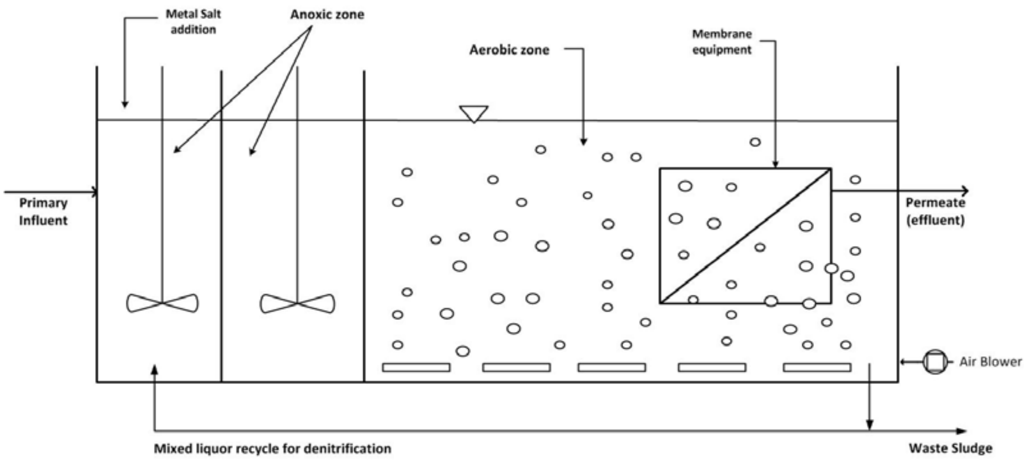

Figure 2: Membrane Bioreactor System Arrangements

Incorporation of anaerobic zones for biological phosphorous removal can also be included (e.g. University of Cape Town configuration). A more common system arrangement nowadays is for the membranes to be housed in a separate tank (**Figure 3**), which has a number of advantages especially with regards to general maintenance and removal of membrane modules.

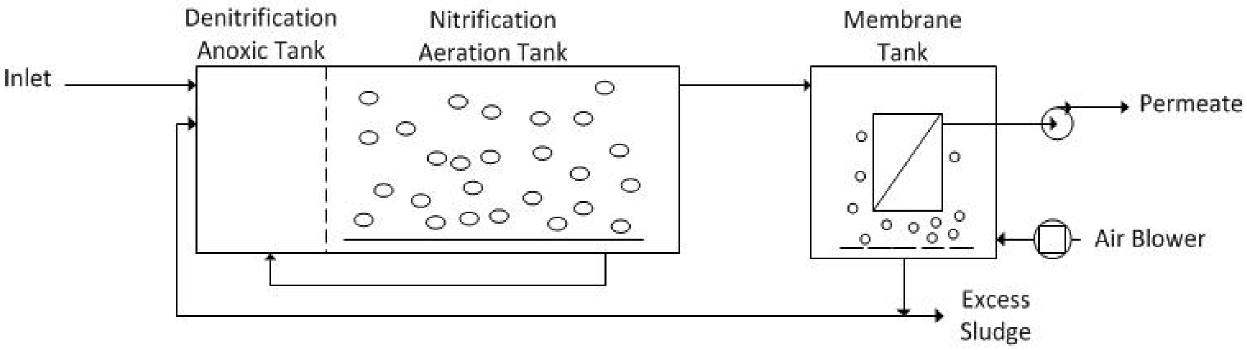

Figure 3: Membrane Bioreactor Sidestream Configuration

MBR plants located in warm climates are less costly than ones with identical capacity located in cold climates. This is due to the effect that liquid viscosity has on the flow rate of a liquid through the membrane pores as viscosity is dependent on temperature. The minimum wastewater temperature is, therefore, a major factor in determining the number of membranes modules required to meet a given MBR treatment capacity (Chapman et al., 2006). Fewer membranes are required where temperatures are higher and, therefore, costs can be reduced in countries with warmer climates.

2.2 Pre-Treatment

Membranes are sensitive to the debris that occurs in raw wastewater e.g. rags and hair etc. and, therefore, must be protected from these and other coarse materials by efficient screening. A lack of adequate screening is known to result in operational problems for MBR plants (Judd, 2011). Typically, screen openings for hollow fibre (HF) membranes are required to be smaller than for flat sheet (FS) membranes as they are more sensitive to clogging (EUROMBRA, 2006). Screen openings range between 1 mm (HF modules) and 3 mm (FS modules) in most facilities (Delago et al., 2011). If the screen is not sufficient, fails, or is bypassed and debris get in, the membranes will clog, causing a reduction in the effective area for membrane filtration. Hollow fibre membranes have a tendency for debris to collect around the top of the fibres and also have a problem with hair pinning, with hairs bridging two pores. Flat plate membrane clogging occurs when debris amasses between the sheets and, if the aeration cannot remove it, sludge accumulates above the blockage, increasing the affected area. Fibres collecting on the aeration system can change the flow pattern and volume of air to the membranes and if the scouring effect is then reduced, the result is increased fouling of the membranes (Reid, 2005).

2.3 Filtration

The ability of the MBR to filter is only limited by the [1]selectivity of the membrane. With time, fouling of the membrane actually increases this selectivity. The flux rate (the flow rate per unit area) through the membrane is affected by the fouling rate (the rate of increase in trans membrane pressure (TMP) with time at constant flux). If fouling continues to the point where the permeability (flux/TMP) decreases beyond set operating criteria then the membranes must be cleaned. The flux below which no fouling is observed is termed the critical flux (Howell, 1995). If the critical flux is reached, significant permeability declines occur. A term more commonly used by practitioners and operators is the sustainable flux, defined as the flux for which the TMP increases gradually at an acceptable rate, such that chemical cleaning is not necessary (Judd, 2011).

Trans Membrane Pressure

The trans membrane pressure for submerged and side-stream MBR pilot systems is calculated as follows:

For submerged MBR systems (e.g. Toray)

$$\textit{TMP (mBar)} = \textit{Static Pressure} - \textit{Dynamic Pressure} \qquad (1)$$

Where: the Static Pressure is measured at zero permeate flow and the Dynamic Pressure is measured with permeate flow

For a side-stream MBR system (e.g. Norit)

$$\textit{TMP (Bar)} = ((\textit{Module Top Pressure} + \textit{Module Bottom Pressure})/2) \qquad (2)$$

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[1] The degree of selectivity depends on the membrane pore size.

Flux

The flux of MBR membranes is calculated as follows:

$$J = \frac{Q_p}{A} \tag{3}$$

Where:

J = Membrane flux (lmh)

A = Total membrane surface area (m^2)

Q_p = Permeate flow rate (m^3/h) x 1000 ℓ

The specific flux or permeability of the membranes is calculated as follows:

$$J_{sp} = \frac{J}{TMP} \tag{4}$$

Where:

J_{sp} = specific flux (lmh/bar)

J = Flux (lmh)

TMP = Tans membrane pressure (bar)

In MBRs, physical cleaning is normally achieved either by backwashing, i.e. reversing the flow, or relaxation, which is simply ceasing permeation whilst continuing to scour the membrane with air bubbles (Judd, 2011).

The net flux for MBR systems using relaxation (i.e. Toray) is calculated as follows:

$$J_{net} = (J \times T_F) / (T_F + T_R) \tag{5}$$

Where,

J_{net} = Net flux (lmh)

J = Membrane flux (lmh)

T_F = Filtration time (min)

T_R = Relaxation time (min)

The net flux for MBR systems using backwashing (i.e. Norit) is calculated as follows:

$$J_{net} = [(J \times T_F) - (J_{BW} \times T_{BW})] / (T_F + T_{BW}) \qquad (6)$$

Where:

J_{net} = Net Flux (lmh)

J = Membrane Flux (lmh)

J_{BW} = Backwash flux (lmh)

T_F = Filtration time (min)

T_{BW} = Backwash time (min)

2.4 Hydraulic and Sludge Retention Time

The hydraulic retention time (HRT, h) is the measure of the time it takes for the incoming fluid to pass through the system and is a function of the reactor volume and the inlet flow rate (Q, m^3/h). The HRT of the MBR system is calculated as follows:

$$HRT = \frac{V}{Q} \qquad (7)$$

Where:

V = Volume of the bioreactor (m^3)

Q = Influent flow rate (m^3/h)

The sludge retention time (SRT) is the measure of the average time that sludge remains within the system. It is defined as the total amount of sludge solids in the system divided by the rate of loss of sludge solids from the system. In general, only the sludge solids in the aeration tank and the waste sludge stream are considered. During operation, mixed liquor suspended solids (MLSS) concentrations within the bioreactor can be kept at a stable level by wasting sludge in planned desludging episodes, maintaining it within its optimum range. SRT is related to the MLSS (mg/ℓ) and the flow rate of waste sludge (Q_w ,m^3/h) by:

$$SRT = V \times \frac{MLSS}{Q_w} \times \frac{1}{MLSS_w} \times = \frac{V}{Q_w} \qquad (8)$$

Where:

SRT = Solids Retention Time (h)

MLSS = Mixed liquor suspended solids concentration in the reactor (mg/ℓ)

$MLSS_w$ = Mixed liquor suspended solids concentration wasted (mg/ℓ)

V = Volume of the bioreactor (m^3)

Q_w = Wasting flow rate from bioreactor (m^3/h)

It is assumed that the solids wasted from the reactor are at the same concentration as those within it.

As the membrane in an MBR rejects all solids, the sludge age can, in theory, be increased continuously. The higher the SRT, the higher the MLSS concentration will be. MBR systems are generally designed at higher SRTs, in the 10 to 30 day range (Melcer et al., 2004). In reality, MLSS concentrations are constrained by an increased membrane fouling potential and the increased operation and maintenance (O&M) cost of aerating a higher mass of biomass.

In addition, measurements of alpha (the coefficient relating oxygen transfer efficiency in process water to that in clean water) in MBR systems clearly show deterioration in oxygen transfer efficiency with increasing MLSS concentrations (Melcer et al., 2004).

2.5 Food to Micro-Organism Ratio (F:M Ratio)

The primary use of any organic matter that enters the bioreactor is for cell maintenance and not for growth or multiplication, such that the MLSS level within the bioreactor reflects the carbon availability in the influent (Reid, 2005). For these reasons, the F:M (food to microorganism concentration) ratios are generally 10–20 times lower (0.02–0.07 kg COD $kg^{-1}d^{-1}$) for MBRs than for conventional activated sludge plants. SRT values for AS plants treating municipal wastewaters are typically in the range of 5-15 days with corresponding F:M values of 0.2-0.4/day. Low F:M ratio implies a high MLSS and a low sludge yield, such that increasing SRT is advantageous with respect to waste generation. The F:M ratio is given by:

$$F:M = \frac{COD \times Q}{MLSS \times V} \tag{9}$$

Where:

F:M = kg COD / kg MLSS.d

COD = Influent COD (mg/ℓ)

Q = Influent flow rate (m^3/h)

MLSS = Mixed liquor suspended solids (mg/ℓ)

V = Volume of the bioreactor (m^3).

Conversion of mg/ℓ to kg/m^3 and hours into days is required.

2.6 Biofilms

Biofilms play an important role in the operation of MBRs. Biofilms form a “cake layer” on the surface of the membrane that enhances the performance of the membrane in terms of nutrient removal through increased metabolism (Livingston and Trivedi, 2006). The impact of the biofilm on performance can be described by Darcy’s Law relating flux to TMP, water viscosity (μ) and the total resistance to water filtration (R_T):

$$J = \frac{TMP}{(\mu \text{ x } R_T)} \tag{10}$$

In equation 10, flux (J) is inversely proportional to flow resistance. If TMP remains constant, the flux will decrease with increased resistance to flow. The total resistance (R_T) is the combined resistance across a membrane and biofilm (cake) and can be described by Equation 11:

$$R_T = (R_M + R_F) + R_C \tag{11}$$

Where:

R_T = total resistance

R_M = membrane resistance

R_F = fouling resistance (pore clogging or adsorption, irreversible fouling))

R_C = biofilm (cake) resistance (reversible fouling)

The R_C has been shown to account for as much as 90% of the total resistance to filtration (Chang and Lee, 1998)

2.7 Fouling

Le-Clech et al. (2006) reported that several factors affect membrane fouling, including membrane materials, mixed liquor characteristics, feed water characteristics and operating conditions. The most significant of these is mixed liquor characteristics, as the ability of the sludge to be filtrated depends on many factors, such as: viscosity, mixed liquor suspended solid (MLSS) concentrations, amount of filamentous bacteria, extracellular polymeric substances (EPSs) and soluble microbial products (SMPs) (Judd and Judd, 2010).

It is widely held that extracellular polymeric substances (EPSs) and soluble microbial products (SMPs) are the main culprits that cause reversible and irreversible biofouling. At a short SRT, polysaccharides, secreted by microbes, in an effort to stabilize their environment and to aid in flocculation, can combine to form colloidal material that subsequently block biofilm pores and increase filtration resistance. (Livingston and Trivedi, 2006). Although SMPs concentrations increase at longer SRTs, there is evidence that the average particle size also increases at higher MLSS and at longer SRTs (Huang et al., 2001). Particle size is important because it determines the rate at which particles migrate away from biofilm due to lift forces induced by air scouring. Thus, bigger (heavier) particles move faster back into bulk solution (mixed liquor) at a constant cross-flow velocity induced by air scouring. (Livingston and Trivedi, 2006).

2.8 Aeration

The bioreactor dissolved oxygen (DO) concentration is controlled by the aeration rate, which provides oxygen to the biomass for the degradation of organics and synthesis of cells. Air passing over the membrane surface is also used for membrane fouling control as it creates a scouring effect and it keeps the biomass mixed and suspended in the bioreactor. Both FS and HF MBRs use coarse bubble aeration underneath the membrane modules to scour the membranes. With the HF design, the membrane moves with the liquid and air flow, whereas with the FS design, the membrane remains fixed during permeation but under relaxation. When there is no permeation with air flow, the membrane material relaxes away from the backing plate and a little movement of the membrane with the air and liquid flow is observed (Judd, 2011).

Abatement of fouling leads to elevated energy demands and has become the biggest contributing factor to operating expenditure (OPEX) in MBRs (Verrecht et al., 2008). Specific aeration demand (SAD_m) is a measure for the amount of air sparging of the membrane in an MBR. Typically, for full-scale plants, the SAD_m will range from 0.3 – 0.57 $Nm^3/h\ m^2$, with FS membranes requiring the less aeration (Judd, 2011).

The specific aeration demand of the membranes based on the permeate flow rate is also known as SAD_p. Minimizing SAD_p minimizes energy consumption to the membrane blowers.

$$SAD_p = \frac{Membrane\ Aeration\ Flow\ Rate}{Flow\ Rate\ of\ Treated\ Water} = \frac{Membrane\ Aeration\ Flow\ Rate}{Flux * Membrane\ Area},\ \left(\frac{m^3\ air}{m^3\ filtrate}\right)\ (12)$$

SAD_p varies greatly from application to application and from one membrane manufacturer to the next (Levasque et al., 2010).

2.9 Cleaning

If a plant is unable to sustain the flux rate that is normally achievable, then fouling is likely to have occurred and cleaning is required to restore permeability. Two options are available, namely a physical cleaning and a chemical cleaning, sometimes combined, that are used to remove what are termed “reversible” and “irreversible” fouling. Reversible fouling is formed by biomass depositing on the membrane surface, creating a caked layer. This is removable through practices such as backwashing (reversing the flow back through the membrane at a higher rate than that of the forward flow) and relaxation (allowing the membrane to be scoured by air whilst allowing no permeation through the membrane). Membrane relaxation encourages diffusive back transport of foulants away from the membrane surface under a concentration gradient, that is further enhanced by the shear created by air scouring (Judd, 2011). Irreversible fouling is caused by the partial or full adsorption of dissolved matter onto the membrane surface. This results in the narrowing or total plugging of pore holes and is generally removed through chemical cleaning with either caustic soda, that dissolves the organic matter and/or hypochlorite, that partially chemically oxidises it. Inorganic fouling is removed with an acid, commonly citric acid, suitable for the membranes and the foulant. A sequence of cleans may be needed if organic and inorganic fouling are present in order to remove all the layers that were not in contact with the chemical during the first clean. Chemical cleaning cannot remove all fouling on the membrane surface. This is known as irrecoverable fouling. Cleaned membranes have lower fluxes than new membranes and therefore irrecoverable fouling dictates the membrane life.

2.10 Membrane Life

There is a correlation between permeability loss and operating time, indicating that the membrane permeability reaches non-operative value after a certain time span. The permeability of the membrane appears to be impacted on most heavily, by inorganic foulants and commensurately by the total mass of oxidant (NaOCl) used during chemical cleanings (Ayala et al., 2011).

2.11 Permeate Water Quality

Because of the small-pore barrier provided by the membranes, MBRs produce high quality effluent, with biochemical oxygen demand (BOD) and total suspended solids (TSS) concentrations of < 2 mg/ℓ (Melcer et al., 2004). Full-scale and pilot scale MBR systems operated with the anoxic/aerobic Modified Ludzack-Ettinger (MLE) biological nitrogen removal process, have achieved effluent total nitrogen concentrations of < 10 mg/ℓ. A summary of typical MBR effluent performance data for other parameters is given in **Table 1** (Wastewater Engineering, 2004 p 1128).

Table 1: Typical performance data for MBRs used to treat domestic wastewater

Parameter	Unit	Typical
BOD	mg/ℓ	<5
COD	mg/ℓ	<30
NH_3	mg/ℓ	<1
TN	mg/ℓ	<10
Turbidity	NTU	<1

Permeate water quality is most often assessed in terms of percentage removal of the contaminant defined as:

$$Removal\ (\%) = 100\ \frac{Co - C}{Co} \tag{13}$$

Where C_o is the influent concentration (mg/ℓ) of a given contaminant at a specific time and C is the corresponding effluent concentration (mg/ℓ)

For the calculation of the removal of microbes and viruses in the MBR system the log removal is used and was calculated as follows:

$$\text{Log removal} = \text{Log}\,(c_f) - \text{Log}\,(c_p) \tag{14}$$

Where:

c_f = Concentration in the MBR influent

c_p = Concentration in the MBR permeate.

2.12 MBR Configurations

MBR systems are available in two different configurations: 'sidestream' or 'submerged', as shown in **Figure 4** (Adham, 1998). In the sidestream configuration (**Figure 4A**), sludge is recirculated from the aeration basin to a pressure-driven membrane system outside of the bioreactor where the suspended solids are retained and recycled back into the bioreactor while the effluent passes through the membrane. In the past, external MBR systems were limited to niche industrial applications involving relatively low flows, due to the high energy cost required to maintain proper cross-flow velocities for sidestream membrane modules (Morgan et al., 2006 and Judd, 2006). But due to recent advances, sidestream MBR systems are now operated with airlift-assisted cross-flow pumping, in which scouring air is introduced along with the sludge recirculation at the bottom of the vertically mounted membrane module to reduce the recirculation flow requirement. In this configuration, the membranes are regularly backwashed to remove suspended solids from building up and are chemically cleaned when operating pressures (TMP) become too high.

In the submerged configuration (**Figure 4B**), a membrane module is submerged in an aeration basin and operated under vacuum. The membrane is agitated by coarse bubble aeration that helps prevent suspended solid accumulation at the membrane surface. The submerged membranes are either regularly backwashed or relaxed and are chemically cleaned when operating pressures become too high (DeCarolis et al., 2009).

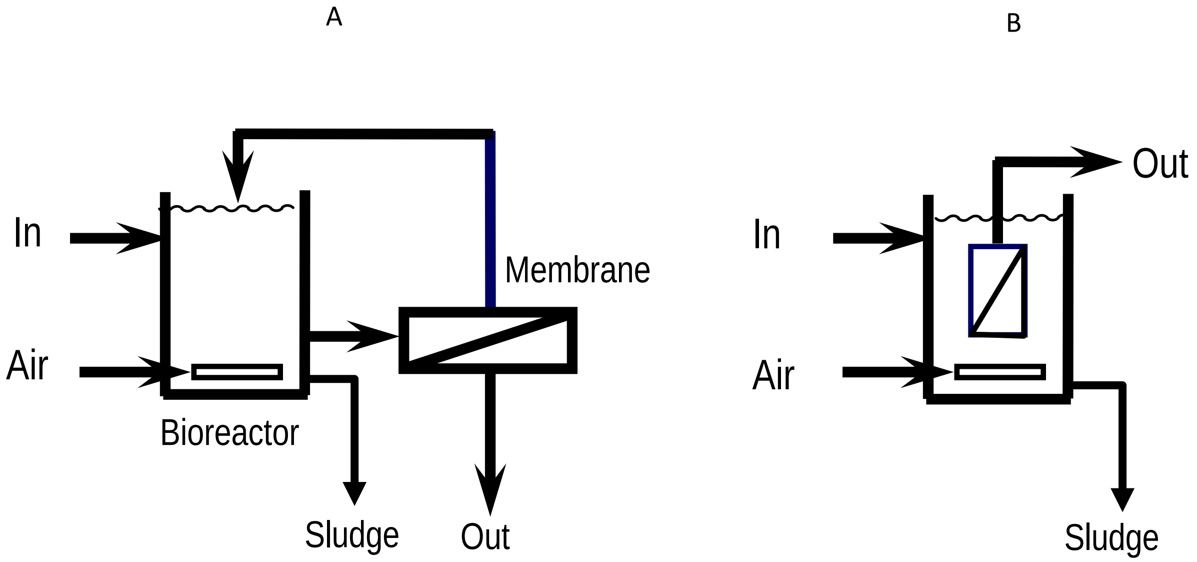

Figure 4 Configurations of a Membrane Bioreactor: A) Sidestream, B) Submerged

The different MBR configurations entail different risks for the operation of the plant. Submerged membranes can either be externally submerged or internally submerged. Externally submerged membranes are located in separate tanks outside the main aeration basin, while internally submerged membranes are located inside the main aeration basin. Thus, if an aeration basin needs to be isolated in an internally submerged plant layout, then all of the biological capacity of the mixed liquor surrounding the membranes and the hydraulic capacity of the membranes within the tank are not available. However, in an externally submerged plant layout, an aeration tank may be isolated and flow to all membrane filtration tanks can be maintained from the remaining aeration basins. Therefore, while the biological activity may be reduced during the maintenance period, the hydraulic capacity can be maintained. This advantage is common to sidestream MBR configurations as maintenance can be undertaken on the aeration basins without impacting on the hydraulic capacity of the plant. Similarly, maintenance on the sidestream membranes can be undertaken without impacting on the biological activity in the aeration basins.

An added advantage of separate aeration and membrane tanks is related to air scouring. Air scouring with coarse bubble diffusers is used to clean the membranes in MBR systems. However, aeration in the bioreactor is achieved using fine bubble diffusers because the oxygen transfer is more efficient than that of coarse bubble diffusers (Melcer et al., 2004). Using separate membrane and aeration tanks allows designers to take advantage of these differences. Whilst a number of membrane configurations exist (**Table 2**), almost all submerged MBR membrane modules are either a rectangular flat sheet (the original being the Kubota product) or vertically-oriented hollow fibres (the original being commercialised by Zenon).

Both submerged and sidestream membrane modules exhibit advantages and disadvantages, as reported by various authors (Cui et al., 2003 and Le-Clech et al., 2006). Flat sheet (FS) modules are less prone to fouling and relatively easy to control but, are more expensive than hollow fibre (HF) modules that are more prone to fouling but can withstand vigorous backwashing (Hashisho etal., 2016)

Table 2 MBR technologies and configurations

		Process Configuration	
		Submerged	**Sidestream**
Membrane Configuration	Flat Sheet (FS)	Brightwater Toray Kubota	Novasep-Orelis
	Hollow Fibre (HF)	Asahi-Kasei Koch Puron Mitsubishi Rayon Pall Corporation Siemens Memcor GE (Zenon)	
	Multitube (MT)	Millennimpore	Norit-Xflow

2.13 MBR Design and Operational Performance

The two key processes common to all MBRs are aeration and permeate withdrawal. The differences between MBRs arise out of the detailed design specifications of the manufacturers which impact on their operational performance parameters such as flux, biomass concentration, permeate quality and specific energy demand. The design specifications that vary between MBR technologies are pre-treatment requirements (screening), membrane material and configuration, aerator design and air/liquid contact, tank design/dimensions and permeation method (suction or gravity). Operation and maintenance (O&M) protocols specified by the suppliers also impact on differences in performance between technologies. MBR products are therefore predominantly differentiated by:

- the precise mode of contact between the membrane and the air introduced from the aerator (i.e. the nature of the air scour), and
- O&M protocols, that include:
    - length of the period between backflushing and/or relaxation (air scouring without permeation)
    - duration of backflushing and/or relaxation
    - nature of chemical clean (frequency of chemically enhanced backwash and/or maintenance clean, composition and strength of chemical reagent), and
- O&M parameters, that include:
    - instantaneous flux
    - backflush flux or pressure
    - MLSS concentration

Since suspended solids are not lost in the clarification step, total separation and control of the solids retention time (SRT) and hydraulic retention time (HRT) are possibly enabling optimum control of the microbial population and flexibility in operation. The membrane not only retains all biomass, but prevents the passage of exocellular enzymes and soluble oxidants creating a more active biological mixture capable of degrading a wider range of carbon sources. High molecular weight soluble compounds (10^3 – 10^6 Da) that are not readily biodegradable in conventional systems, are retained in the MBR. Thus, their residence time is prolonged and the possibility of oxidation is improved (Cicek, 2003).

Typical operation flux rates for various full-scale immersed MBRs applied to treat municipal wastewater treatment are over 19 – 20 lmh (Judd, 2010) with a peak flux (< 6h) in the range 37 -73 lmh (Asano et al., 2006). A recent analysis of design and operation trends of the larger MBR plants in Europe (Lesjean et al., 2009), shows a broad difference between the design and operation flux. For Kubota systems, the design maximum daily net fluxes are 14-48 lmh (mean 32 lmh) while for the GE Zenon modules they are 20-37 lmh (mean 29 lmh). However, it is interesting to note that for both systems the operation net flux is over 18 lmh. (Delago et al., 2011). This highlights the fact that the operational flux can be considerably lower than the design flux reported by the manufactures. Design specifications should therefore be used with caution and if possible should be confirmed with pilot testing.

CHAPTER 3: LITERATURE REVIEW MBR APPLICATIONS

3. MBR

The market share of membrane bioreactors (MBRs) in the field of biological wastewater treatment has increased significantly in the last decade, as reported by various authors (Judd, 2011; Lesjean et al., 2011). With this steady growth, MBRs are considered a key technology for future wastewater treatment and reuse schemes (Lesjean, 2009). MBRs have been reported by Li et al. (2009) as the only technology able to achieve satisfactory removal efficiencies of organic substances, surfactants and microbial contaminants, without a post filtration and disinfection step. MBRs have been reported to outperform conventional activated sludge (CAS) and produce a superior effluent quality in a number of studies (Sutherland, 2010; Naghizadeh et al., 2011 and Hashisho et al., 2016). Membrane filtration ensures higher removal efficiency for suspended solids (SS), bacteria, chemical oxygen demand (COD), and [2]trace organics (Zhu and Li, 2013). The accumulation of nitrifying bacteria due to membrane rejection, provides higher efficiency and stability for ammonia removal. In addition, membrane filtration is better than sedimentation in separation efficiency and stability (Sun et al., 2015).

There is a perception that an activated sludge plant bioreactor operated at extended sludge ages is the same as an MBR bioreactor. Smith et al. (2003) conducting experiments on CAS and MBR pilot plants operated under the same conditions and sludge ages, proved that this was not the case. It was observed in terms of both biokinetic and macroscopic performance data that suggest the inclusion of a membrane in the process alters the fundamental nature of the bioreactor. A clear benefit of these differences is that MBRs appear to be more robust with respect to changes in operation.

De Luca et al. (2013) investigated the effectiveness of MBRs and conventional activated sludge plants (CASP) in removing bacteriophages (viral indicator) and bacterial faecal indicators (E.Coli) from

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[2] Trace organics is a generic term encompassing pharmaceuticals and personal care products (PPCP), pesticides and other potential endocrine disrupting compounds (EDCs).

municipal wastewater and found that MBRs could achieve as much as 2.7 log removal value (LRV) higher than CASP. A number of other studies (Zhang and Farahbakhsh 2007; Simmons and Xagoraraki, 2011) found that CASP may not be sufficient to remove micro-biological contaminants to levels safe enough for wastewater to be discharged to the environment. CASP commonly have a chemical disinfection step such as the addition of chlorine (as is the case at Darvill WWW) to the final effluent to kill micro-organisms and pathogens. This practice has the potential to have negative environmental impacts due to the generation of harmful disinfection bi-products e.g. THM, and the addition of chemical residues (Chen and Wang, 2012). There is no chemical disinfection required following MBR treatment.

In summary, MBRs offer a number of advantages over conventional treatment technologies that make them attractive as a treatment technology choice. These include improved effluent water quality, the ability to treat high organic loads, a smaller footprint, lower surplus sludge production, effluent disinfection and a complete decoupling of the hydraulic and sludge retention times (Stephenson et al., 2000; Smith et al., 2003; Kang et al., 2008; Kraume; Drews, 2010 and Kim et al., 2011). Additionally, water reuse using MBRs is prevalent in many countries (Trinh et al., 2016 - Part 2).

The advantages offered by MBRs, especially the ability to treat high organic loads, was a motivating factor in choosing MBRs as a technology worth trialing at Darvill.

The disadvantages associated with MBRs are mainly cost related. High capital costs due to expensive membrane units and high energy costs due to the need for a pressure gradient, have characterized the system. Concentration polarisation and other membrane fouling problems can lead to frequent cleaning of the membranes which stops operation and requires clean water and chemicals. Another drawback can be problematic waste activated sludge disposal. Since the MBRs retain most suspended solids and higher molecular weight organic matter, waste activated sludge may exhibit poor filterability and settleability properties. Additionally, when operated at high SRTs, inorganic compounds accumulating in the bioreactor can reach concentration levels that can be harmful to the microbial population or membrane structure (Cicek, 2003).

One of the MBRs key design criteria is choosing the operating flux. As with all membrane systems, this decision impacts directly on both capital expenditure (CAPEX) and OPEX. Higher membrane fluxes allow a reduction in membrane area and therefore CAPEX, but have the concomitant effect of increasing the membrane fouling rate. Aeration demand and the frequency of cleaning have to be increased to control the associated fouling that results in increased OPEX.

3.1 MBR Technology in South Africa (Perceived barriers to adoption)

Although there are many examples of the use of MBRs internationally, their use in South Africa is still very limited. The history of MBR use in South Africa is very brief and at the time this study was proposed there were very few MBR projects that could be referenced. South Africa's first MBR plant of significance was implemented at the Illovo Sugar Mill in Sezela, KwaZulu-Natal using Kubota flat sheet membranes. The plant was commissioned in 2005 and has a capacity of 1.2 Mℓ/day (Hai et al., 2014). More recently the largest MBR plant in South Africa was built at Zandvliet in the Western Cape in 2009. The plant treats municipal wastewater in parallel with a conventional secondary treatment process. The MBR plant has a capacity of 18 Mℓ/day and uses Zee-Weed ZW500D Hollow Fibre (HF) membrane modules (Hai et al., 2014). Further MBR plants have since been constructed in the Western Cape at Malmesbury (20 Mℓ/day) and Belville (40 Mℓ/day). The Malmesbury MBR plant is discussed in more detail in **Section 3.4.7**. In the Eastern Cape, the Nelson Mandela Bay Metro is planning a direct industrial water reuse project: This project, which is in its design phase, will provide 45 Mℓ/d of direct industrial water reuse via membrane biological reactors at the Fishwater Flats WWTW.

Information on the use of MBRs in industrial water treatment in South Africa is equally scarce and only one research paper on the treatment of an industrial effluent was found. Edward et al. (2003) studied the degradation of synthetic xylan effluent using a membrane bioreactor. There are, to the author's knowledge, only a small number of industrial MBRs in operation throughout the country including a 0.5 Mℓ/day capacity plant using Toray Flat Sheet (FS) membranes at a textile factory in Pietermaritzburg.

Some of the perceived barriers to the adoption of MBRs in South Africa may be the reported higher economic cost when compared to conventional activated sludge treatment, one of the major economic considerations being the membrane price and membrane life expectancy. The performance of MBRs are not always reported as being superior to conventional activated sludge treatment. Yoon et al. (2004) compared MBRs with combined biological and chemical processes (CBCP) and found the MBR system to be less economical and that the effluent water quality could not be greatly improved compared to that of the conventional biological and chemical process.

Another important factor that may influence the widespread application of MBRs is membrane fouling (Bani-Melham and Smith, 2012). Membrane fouling leads to a decrease in flux, which in turn requires higher aeration demand to scour the filtration biosolids and potentially more frequent membrane cleaning and replacement. These factors increase the operational cost (Kim et al., 2011). Consequently, the MBR operational costs (due to high energy consumption or chemicals required for membrane cleaning) can hamper the application of MBRs globally (Mannina and Cosenza, 2013).

The uptake of MBR technology to treat domestic and industrial wastewater in Europe has been driven by increasingly stringent regulatory discharge standards (Di Trapani et al., 2014). South Africa has its own regulations for wastewater discharges as defined by the National Water Act (1998) General Authorization standard. Stricter and more specific standards may apply depending on the situation.

Despite these discharge standards, South African wastewater works have very poor compliance. The latest compliance survey (DWS, 2013), known as Green Drop, indicates that 70% of wastewater works in South Africa are not compliant. In this environment where not much is done to improve the treatment of wastewater, there is a lack of innovation and adoption of new technologies, such as MBRs, that can improve effluent water quality. In South Africa there are still many people without access to safe drinking water who still use river water for drinking purposes, thus improving sewage effluent discharge quality should be a priority. One of the advantages of MBRs that was mentioned previously, is that it removes pathogens, thus reducing the potential microbiological risk and possibility of infection from water borne diseases.

Tighter discharge standards requiring improvement in the effluent water quality and space limitations were some of the reasons decision makers opted to upgrade the Malmesbury WWW with MBRs (Ramphao et al., 2013). However, the implementing consultants (Aurecon Pty (Ltd)) indicated that in general it is very difficult to introduce new technologies into South Africa through the current tender system (Ramphao et al., 2013).

Another factor to consider is the generally conservative nature of the water and wastewater industry that has been classified alongside the food, beverages and oil industries as low-tech (technology using equipment that is relatively unsophisticated). Within the OECD (Organisation for Economic Cooperation and Development) business classification, technology utilization and trends, water industries are not mentioned (Thomas and Ford, 2005), implying a lack of innovation and an industry rooted in conservatism. The implication is that the introduction of MBR or other innovative technologies in South Africa and the water industry, in genera,l may be difficult.

3.2 Reason for Pilot Testing and Limitations

Pilot tests have many benefits in confirming the correct design philosophy and reducing project cost and risk. Pilot testing was separated into two well-defined categories by Layson (2000), as defined in **Table 3**.

Demonstrations:	are short on-site tests that demonstrate the technology and indicate the quality of treated water that can be achieved. They should not be used as a basis of final plant equipment sizing or overall process design;
Pilot Testing:	is a well-planned programme designed to investigate the expected operating conditions of a full scale plant.

Table 3 Characteristics of demonstration and pilot testing (Layson, 2000)

Type	Demonstration	Pilot Testing
Duration	1 day to 2-3 weeks	1-12 months
No. of clean cycles	< 2	2 or more
Feed analyses	Scant (e.g. Turbidity & colour)	Regular detailed feed water analysis
End user involvement	Little or none	Good – ideally the end user runs the trial with assistance from the equipment vendor
Event logging	Little or none	Logging of events/upsets and explanation of causes
Planning and reporting	Little or none	Detailed trial protocol written before the trial commences. Detailed final trail report written.
Other	N/A	May include repeated runs to investigate impact of variables e.g. alternative coagulants, different feeds etc.

The Darvill study fulfills the characteristics of pilot testing, with one exception. A shortcoming of the study was the lack of a detailed trial protocol. A limited trial protocol was in place and this is elaborated on in **Chapter 4 Project Design**.

Membrane fouling is a serious problem in MBR processes which limits the widespread application of MBRs. The prediction of MBR fouling and the determination of the membrane chemical cleaning interval has become increasingly important in recent years, according to Kim et al., (2011). Most membrane cleaning protocols are given by the manufacturer, however, the conditions under which these are determined are either not known or are confidential. The applicability of the cleaning intervals provided for other sites and systems is therefore assumed. Actual cleaning intervals may be shorter or longer, but this can only be confidently established with piloting. This was borne out by the results obtained from this research.

The other critical aspect to consider is the choice of permeate flux rate for design purposes. Sustainable flux rates are impacted on by a number of factors including fouling, cleaning protocols, aeration, feedwater characteristics and biological conditions. As a result, deciding on a sustainable permeate flux rate relies on the analysis of empirical data obtained from pilot or full-scale experiments. Pilot testing does have its limitations and caution should be taken when scaling-up results to full-scale plants.

Kang et al. (2008) found that the performance of a system at one scale is not a predictor of the performance of a system at another scale. Yang et al. (2006) concurred with this declaration stating that results from bench or pilot scale experiments were not always correlated to the application in full-scale systems. Kang et al. (2008) goes on to say that in reality, industries have been reporting a drastic drop in efficiency when pilot scale experiments are scaled up into full-scale plants. These experiences imply that there are large differences in the performance of pilot and full-scale systems and researchers should be aware of these limitations. The reasons for these differences are varied, ranging from complex mass and heat transfer limitations to operational issues. For example, on full-scale plants the biological aeration is optimized using sophisticated supervisory control and data acquisition (SCADA) systems. The aeration efficiency can, therefore, be improved resulting in significant operating cost savings. These operating efficiencies are not readily achievable on pilot plants, most notably because of a lack of system and human resources. This is further illustrated in research conducted by Phan et al. (2015) where removal of organic contaminants by pilot and full-scale membrane bioreactors is compared. The MBR systems demonstrated similar reduction of chemical oxygen demand (COD). However, the full-scale MBR sustained higher and more stable nutrient removal (>95 % for both total nitrogen (TN) and phosphate, (PO_4^{-3}-P) than the pilot-scale system (ca. 80 % TN and 30 % PO_4^{-3}-P)).

Sun et al. (2015) discusses the issue of scale through research in a laboratory or pilot scale and how results drawn from these studies relate to performance on full-scale plants. The scale of the system studied might substantially affect wastewater treatment performance, as well as mixed liquor characteristics according to research (Drews et al., 2006). Sun et al. (2015) highlights certain study conditions that will aid in results being representative and transferrable.

These include:

- systems must be run in parallel to ensure accuracy of comparison;
- studies should be conducted over multiple seasons, so that the impact of temperature changes are accounted for.

3.3 Data Analysis Techniques

The case studies described below use similar techniques to analyze the performance of different MBR pilot plants and full-scale plants. This was done by analyzing the permeate water quality (physico-chemical and microbiological) and by measuring operational parameters such as flux rate and TMP. The quantitative assessment of permeate water quality is normally achieved by the calculation of the percentage removal of the relevant contaminant (Refer to Section 2.11). Comparison of results derived from these studies is thus made possible. When comparing performance, this methodology was by far the most prevalent in the literature.

In other MBR studies statistical analysis was used on occasion, including analysis of variance (ANOVA) testing and multiple regression analysis. A standard one-way ANOVA test is used in order to compare microbial contamination removal in conventional activated sludge plant (CASP) effluent and in MBR permeate at a significant level of $P \leq 0.05$ (De Luca etal., 2013). Multiple regression analysis is used when comparing particular relationships between variables to determine their dependency, such as sludge morphology and sludge filterability (van den Broeck et al., 2011).

More sophisticated statistical methods are applied when used for predictive modelling purposes. Kim et al. (2011) use the recursive least squares method (RLS) to compare the predictive accuracies of different fouling prediction models.

The use of statistical methods to compare the performance of different MBR configurations appears to be lacking in the literature and hence this study aims to apply the Student t-test (comparison of means) and F-test (comparison of variance) to the data. The literature search was not exhaustive, but the only equivalent approach that could be found was in a performance comparison between HF and FS MBRs in which Hashish et al. (2016) used the paired Wilcoxon signed-rank test.

This study goes further in analyzing the reliability of performance of the two MBR pilot plants and Darvill WWW by using a reliability analysis method developed by Niku et al. (1979). Niku et al. (1979) analyzed thirty seven activated sludge treatment plants by using a probabilistic approach to predict performance and reliability. The method has since been used by various authors including Gupta and Shrivastava (2006); Oliveria and Sperling (2008) and Djeddou et al. (2013). The research performed by Oliveria and Sperling (2008) is of particular relevance as they applied the methodology to six different treatment technologies to compare their performance and reliability. Activated sludge was one of the technologies, but MBRs were not included. In the literature review undertaken, no studies could be found that applied this method of reliability analysis to MBR technology.

3.4 Previous Research (Case study reviews)

MBR research was grouped into six categories by Yang et al. (2006) based on a review of worldwide scientific publications, namely 1) literature and critical reviews, 2) fundamental aspects, 3) municipal and domestic wastewater treatment, 4) industrial wastewater and landfill leachate treatment, 5) drinking water treatment, 6) others. The major areas of study were membrane fouling, operation and design parameters, sludge properties, microbiological characteristics, cost and modelling. Many studies in categories 3) -6) focused on applied research and general MBR performance.

With respect to the latter, a number of studies have been undertaken around the world comparing the performance of different MBR systems at pilot scale and full scale. The chief focus of these studies is on the final or permeate water quality produced. A common set of target water quality parameters predominates this research making comparison between studies possible (**Refer to Section 2.2.10**). The research in this area (MBR pilot testing) is very often driven by regulatory pressures where discharge standards have been tightened and alternative technologies are being tested to achieve these standards. The assumption is that existing water treatment processing is failing to meet these standards in some way or that newer technologies can do this more effectively.

The case studies presented here highlight the types of pilot studies that have been undertaken and summaries are given of the performance of MBR systems in treating mainly domestic sewage. The performance criteria are based on the output water quality achieved, but other operational factors that would impact on the performance are also highlighted.

3.4.1 Point Loma, San Diego MBR pilot study (2004)

Four commercially available MBR systems were operated at a pilot scale to investigate their performance in the reclamation of municipal wastewater. The four MBR systems were supplied by US Filter; Kubota Corporation; General Electric (GE) (Zenon); and Mitsubishi Rayon Corporation, for a 16 month period. All the MBRs are submerged systems, with three of the systems (US Filter, Zenon and Mitsubishi) using HF membranes and the Kubota MBR system using FS membranes. In addition, based on the nominal pore size, three of the membranes (US Filter, Kubota and Mitsubishi) can be classified as microfiltration, while GE (Zenon) membranes are ultrafiltration. The MBR systems were operated at permeate fluxes between 20 and 41 lmh (DeCarolis and Adham, 2007).

A summary of the effluent water quality over the entire study for the four MBR systems tested is provided in **Table 4**. Overall, each system produced effluent low in particulate (i.e. turbidity < 0.1 NTU); organics (i.e. BOD < 2 mg/l, COD < 25 mg/l, and TOC < 7 mg/l); and microbial contaminants (i.e. total coliphage, 13 PFU/100 ml). The ammonia concentrations measured in the effluent of all systems were also low (i.e. 0.25 to 3.1 mg/l-N) throughout the study, indicating that the systems achieved high levels of nitrification. As expected, the concentration of nitrate in the Kubota MBR effluent was much lower (average = 2.9 mg/l-N) than in the other systems tested (average = 20 mg/l-N) because it was the only system that contained both aerobic and anoxic zones allowing for nitrification/denitrification. As shown in Table 2.4, the average concentration of total coliforms measured in the effluent of the Zenon (807 MPN/100 ml) and US Filter (386 MPN/100 ml) MBR systems was noticeably higher than the concentration measured in the other MBR systems (13 MPN/100 ml).

Table 4: Point Loma MBR effluent water quality data (2004)

Water Quality Parameter	Units	US Filter Average	Kubota Average	GE (Zenon) Average	Mitsubishi Average
Particulate					
Turbidity	NTU	0.04	0.08	0.06	0.07
Nutrients					
Ammonia-N	mg/l-N	0.25	0.6	0.71	3.1
Nitrate-N	mg/l-N	23.6	2.95	21.6	15.2
Nitrite-N	mg/l-N	0.03	0.02	0.02	0.5
Orthophosphate-P	mg/l-P	0.41	0.15	0.66	0.67
Organics					
[3]BOD_5	mg/l	<2	<2	<2	<2
COD	mg/l	20.5	18.4	17.3	23.2
TOC	mg/l	5.8	6.5	6.8	6.9
Microbials					
Total Coliform	MPN/100 ml	386	13	807	7
Faecal Coliform	MPN/100 ml	50	3	9	2
Total Coliphage	PFU/100 ml	13	10	1	13

After further testing, it was determined that the high total coliform counts in the GE (Zenon) system could be attributed to contamination on the permeate side of the membranes. This was confirmed by disinfecting the permeate piping of the system midway through the testing period, after which total coliform counts were consistently less than 2 MPN/100 ml (DeCarolis and Adham, 2007).

3.4.2 Broad Run water reclamation facility MBR pilot study (2005)

A MBR pilot plant was operated to determine the capability of MBR to produce an effluent sufficient to meet the low-nutrient effluent standards required for Chesapeake Bay, United States of America. The average influent flow to the pilot plant was 3.2 m^3/h which provided a total average HRT of 8.8 hours and a membrane flux of 34 lmh. The permeate results achieved are provided for in **Table 5** below.

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[3] BOD_5 – The standard oxidation test period for biochemical oxygen demand (BOD) is 5 days.

Table 5: Broad Run MBR effluent water quality data

Parameter	Units	Primary Influent	Permeate (Mean)
BOD_5	mg/ℓ	133	< 2
TSS	mg/ℓ	82	1
COD	mg/ℓ	283	18
TOC	mg/ℓ		6.1
TKN	mg/ℓ	36	1.3
NH_3-N	mg/ℓ	21	< 1
[4]TP	mg/ℓ	5.5	
Turbidity	NTU		0.02
Total Coliforms	CFU/100 mℓ		5
E.Coli	CFU/100 mℓ		0
BOD_5/TKN	Ratio	3.8	

Problems were experienced with the transfer of oxygen to the anoxic zone from the aerobic zone in the pilot system that limited pilot-plant nitrogen removal capabilities. These constraints of the pilot plant could be addressed in a full-scale facility (Fleischer et al., 2005). Additionally, the influent wastewater was relatively low-strength for nitrogen removal processes as illustrated, but its BOD_5/TKN ratio of 3.8. Based on the results, the MBR pilot plant demonstrated the capability to reliably produce effluents with low nutrient concentrations.

3.4.3 Coill Dubh MBR installation (2005)

A new MBR plant was installed at an aging facility to improve the quality of the effluent discharge into the local river and produce a potential source of reclaimed water. The MBR using immersed flat sheet technology by MEMBRIGHTR, was designed to operate at a gross flux of 27 lmh and a maximum TMP of 300 mbar. The MBR permeate quality exceeds the legislated discharge requirements and is often below detection limits. Average permeate results are: 5 mg/ℓ BOD, 5 mg/ℓ SS, 0.5 mg/ℓ NH3-N and 0.05 mg/ℓ TP. Both MBR and conventional activated sludge processes were investigated during the pre-design, but MBR technology was selected due to the high quality of MBR effluent (Melcer and Tam, 2006).

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[4] TP – Total Phosphorous; TKN – Total Kjeldahl Nitrogen

3.4.4 Point Loma, San Diego MBR pilot study (2009)

The U.S. Bureau of Reclamation undertook a study in 2009 to evaluate four newly developed MBR systems for water reclamation. The four MBR systems were Puron™ MBR from Koch Membrane Systems, Huber® MBR from Huber Technology, Toray MBR from I. Kruger Inc. and Norit MBR from Parkson Corporation. Each MBR pilot system was operated for a target period of about 3,500 hours on raw wastewater from Point Loma Wastewater Treatment Plant in California. In addition, a RO membrane, provided by Koch Membrane Systems, was also evaluated while operating on MBR effluent.

The results obtained from the pilot study indicated a significant difference in the operating flux of the submerged MBR systems (Puron, Huber, and Toray) compared to the external MBR system (Norit). The median net flux for the submerged MBR systems measured between 22–27 lmh whereas the median net flux for the external MBR system measured 46 lmh. The high flux operation of the external MBR system may be attributed to better turbulence available within the external membrane module due to a relatively higher recirculation flow requirement compared to submerged MBR systems. All four MBR systems tested produced excellent water quality with effluent turbidity of less than 0.1 NTU and effluent 5-day biochemical oxygen demand (BOD_5) concentration of less than 5 mg/ℓ. When tested for microbiological contaminants removal, all four MBR systems achieved more than 5-log removal of total and fecal coliforms, and more than 3-log removal of inherent coliphage. The MBR systems also achieved ammonia levels of less than 0.5 mg/ℓ-N in the effluent, indicating complete nitrification. The denitrification efficiencies of the systems varied depending on the presence of an anoxic zone, with permeate nitrate concentrations varying from 4.2–29.3 mg/ℓ-N (DeCarolis et al, 2009). The water quality results are summarized in **Table 6**.

Table 6: Point Loma MBR effluent water quality data (2009)

	Puron	**Huber**	**Toray**	**Norit**
Permeate	Nitrification	Nitrification	Nitrification	Nitrification/Denitrification
NTU	0.09	0.05	0.06	0.04
BOD_5 (mg/l)	<2	<5	<2	<2
NH_3-N (mg/l)	0.3	0.2	0.2	0.2
NO_3 (mg/l)	29.3	15.2	9.8	4.2
NO_2 (mg/l)			<1.52	<1.52
TIN (mg/l)	31.1	16.7	16.7	6
TC (CFU/100ml)	100 (5-log)	<9 (6-log)	<10 (6-log)	<20 (6-log)
FC (CFU/100ml)	<10 (5-log)	<8 (5-log)	<12 (5-log)	<10 (5-log)
Coliphage (CFU/100ml)	<10 (5-log)	<9 (3-log)	<11 (3-log)	<10 (3-log)
Virus (log removal 50thile)	1-log	4-log	3-log	4-log

3.4.5 Ulu Pandan Bedok water reclamation plant, Singapore

The success of the MBR trials at Bedok led the Singaporean Public Utilities Board (PUB) to construct a 23 Mℓ/d demonstration plant that was commissioned in December 2006. The plant is fed with settled sewage, which receives wastewater of roughly 90% domestic and 10% industrial origin, a mix of roughly the same proportions as Darvill wastewater.

The pilot trials were conducted on three MBR pilot plants operating simultaneously. The three MBR technologies are not known, but have been postulated by Judd, 2011 to be those of Kubota, GE (Zenon) and Mitsubishi Rayon (MRE) based on their membrane properties. The mean product water quality from each of the MBRs tested was found to be broadly similar and is presented in **Table 7**. Pilot testing has shown that MBRs produce a slightly superior quality product water than secondary treatment followed by UF/MF, specifically with respect to TOC, nitrate and ammonia (**Qin et al., 2006**), and also tends to be lower in cost.

Table 7: Ulu Pandan Bedok effluent water quality trial data

Parameter (Mean)	MBR	UF
NTU	<0.2	–
TKN (mgl^{-1})	<2	4.5
NH_4-N (mgl^{-1})	<1	3
TOC (mgl^{-1})	<5	7

3.4.6 West Tehran water and wastewater company MBR pilot study

Naghizadeh etal. (2011) ran submerged MBR pilot plant tests on domestic municipal sewage with an industrial component. The MBR achieved COD (< 10 mg/ℓ), TSS (< 1mg/ℓ) and turbidity (< 0.3 NTU) removal rates of 96%, 99%, 99.5% respectively. The quality of the effluent was such that the authors stated that the effluent could be directly fed to an RO system for reuse applications.

3.4.7 Malmesbury municipal MBR plant, South Africa

The benefits of a reduced footprint and new discharge standards were two of the major reasons engineers chose MBR technology for the upgrade of the Malmesbury WWTW in the Cape in 2010. Four outside-in hollow fibre (HF) membrane modules were installed. The capacity of the Malmesbury WWTW was increased from 5.5 Mℓ/day to 10 Mℓ/day. The design average flux rate is 31 lmh, with a peak flux rate of 36 lmh. Ramphao etal (2013) reported consistently high removal efficiencies in excess of 97% for COD, NH_3-N, TKN and TSS, while P removal exceeded 93%. Removal of indicator bacteria coliforms (E.Coli) was good, with only four out of eighteen samples exceeding the 80th percentile discharge requirement (> 6 E.Coli/100 mℓ).

3.4.8 Conclusions

From the case studies presented, the following is noted:

- The mean product water quality of MBR systems appears to be broadly similar and consistent;
- The product water is of a high quality and can be released safely into the environment and be used as a feed for downstream reclamation processes such RO;

- MBR systems produce a better final water quality than conventional treatment coupled with UF and are more economical, as was recorded at the Bedok Reclamation Plant;
- MBR systems designed to treat domestic sewage are robust enough to cope well with some industrial sewage content in the influent.

CHAPTER 4: PROJECT DESIGN AND METHODOLOGY

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4. PROJECT DESIGN AND METHODOLOGY

4.1 Pilot Plant Objectives

The main objectives of this research are:

(1) To compare the relative performance of two MBR configurations operated in parallel to the Darvill WWW in terms of the following:

a) Permeate flux (sustainable flux rate)

b) Maintenance requirements (backwash/relaxation frequency, cleaning in place (CIP))

c) Quantification of the treatment efficacy by measuring the removal efficiencies of specific pollutants

(2) To compare the relative performance of two MBR pilot plants with the conventional treatment process used at Darvill WWW in terms of effluent quality and process reliability.

(3) Establish the peak sustainable flux rates of the membranes.

4.2 Planning

The following actions were taken to ensure the effective undertaking of the pilot study:-

- A dedicated project leader was given responsibility for the management and execution of the project
- Key stakeholders were included in the planning of the project and formed part of a project steering committee (PSC). The PSC met once a month for the duration of the project. The stakeholders included operations staff, process engineers, technology suppliers, laboratory staff and on occasion senior management.

- Technical working groups were also established to discuss practical issues and problems that might arise and to provide support where necessary.
- Cleaning chemicals were ordered in advance and stored in a secure environment ready for use.
- All services required to operate the plant were installed prior to commissioning the pilot plants. These included power, feedwater supply, telecommunications (remote control), potable water and disposal of waste streams.
- Arrangements were set in place with laboratory services so that they could dedicate resources to the project and have the required materials and equipment ready.
- Dedicated operators were employed on contract and trained. Detailed instructions were provided to them to meet the project objectives.

The candidate initiated the project; obtained funding and project managed all aspects of the project. From inception, this included the project plan, budget, programming, resourcing, technology choice, acquisition of technology, pilot plant installation and procurement of ancillary infrastructure e.g. pumps and pipelines. During the project the candidate was responsible for supervising the sampling programme, water quality data verification, pilot plant monitoring and control (changing set-points), parameter (flux) adjustments, assisting with fault finding, maintenance, procurement (chemicals) and CIPs and all other decision making regarding the operation of the pilot plants. In terms of meeting the project objectives the candidate was responsible for all data collation, application of statistical methods to interpret data, and drawing conclusions regarding the MBR performance and final reporting.

4.3 Trial Period

The trial period of 12 months was estimated as the time required for evaluating the MBRs effectively. This period was chosen so that the pilot plants would be operated for a year through all seasons and therefore their performance would be representative of changing operating conditions e.g. temperature. Other reasons that made this trial period appropriate were:-

- Three to four weeks was required to allow the biological system to acclimatise.
- An extended period of operation was required so that the performance of the MBRs could be evaluated under changing feed water conditions as might be experienced during pollution incidents. There was no way of knowing when these pollution incidents would occur and therefore the likelihood of capturing an incident was increased through a lengthy period of operation.

- Twelve months of operation was required as some manufactures claimed that the membranes only required a chemical clean every 6 months. The operational period thus had to be inclusive of at least two cleaning events to be able determine the effectiveness of the cleaning and whether this reported cleaning frequency was accurate.
- Establishing the critical flux required stable conditions. As it was not known how long achieving operational stability would take, adequate time needed to be made available to cater for disruptions to the process e.g. breakdowns.
- Peak flux performance tests were also planned which would require additional time

4.4 Test Site

The testing site is the Darvill Wastewater Works (WWW) in Pietermaritzburg, Kwa-Zulu Natal, South Africa, which is owned and operated by Umgeni Water. The Darvill WWW is a traditional activated sludge wastewater treatment plant, consisting of primary and secondary wastewater treatment processes (**Figure 5**).

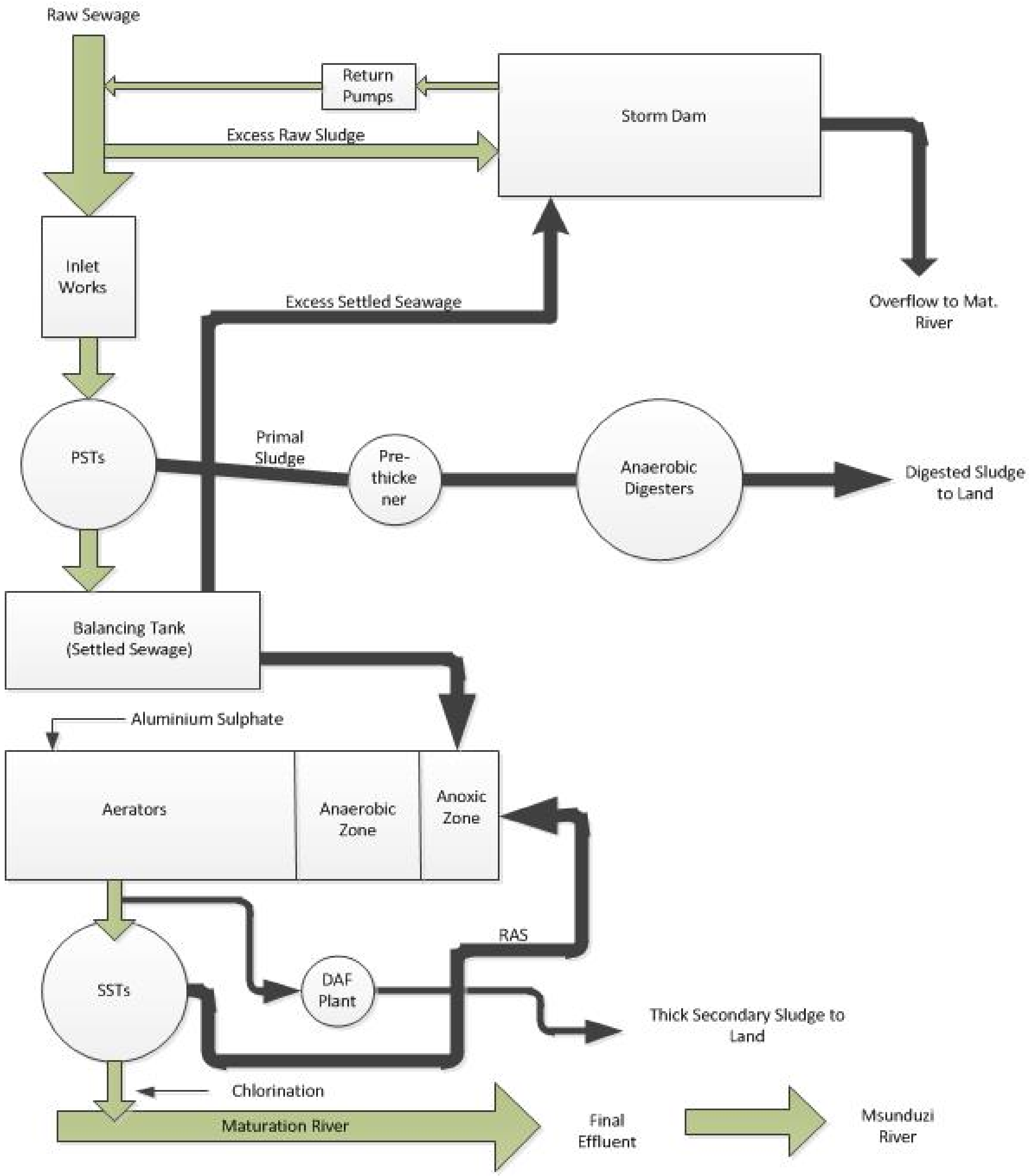

Figure 5: Darvill WWW Process Flow Chart

The plant comprises the following unit Processes (GOBA, 2013):

- Storm water overflow and storage facility
- Excess storm water chlorination facility and storm return pump installation
- Inlet works complete with mechanical screening, grit removal and flow measurement
- Primary sedimentation tanks
- Bio-filters (decommissioned)

- Activated sludge process with anaerobic, anoxic, and aeration zones in the aeration tanks for nutrient removal
- Aluminum sulfate addition to assist phosphate removal
- Secondary clarifiers for separation and return of activated sludge
- Chlorination of final effluent
- Pre-thickener for primary sludge
- Dissolved Air-Flotation Tanks
- Anaerobic digesters

The existing inlet works consists of two inlet channels each equipped with hand racked coarse screens, four mechanical screens installed in pairs, four vortex flow grit separators complete with submersible centrifugal grit pumps, grit classifier and belt conveyor with screenings compactor and flow measurement.

Primary treatment consists of three primary settling tanks (PST), two nominally 30 m diameter and the third 40 m diameter. Primary sewage is fed from the PSTs to a balancing tank (10 Mℓ).

Primary settled sewage is transferred and lifted from the balancing tank by the main pump station to an elevated level at the activated sludge tanks inlet from where the sewage receives secondary treatment. The pump station consists of two receiving sumps with two large horizontal split casing centrifugal pumps servicing each sump. A central manifold connects the two pump sets to allow for interchangeable operation. The two pumps per sump operate in a full duty/standby configuration.

The activated sludge plant at Darvill consists of a number of pre anoxic / anoxic / anaerobic zones followed by the aeration basin. The aeration basin is equipped with 15 x 75 kW vertical shaft surface aerators and nine low speed mixers in the anoxic/anaerobic/aerobic zones. The biological reactor has a retention time of 9.2 hours for a flow of 60 Mℓ/day which is adequate for a conventional activated sludge process; therefore hydraulically the biological reactor is adequately sized. At a COD and TKN concentration of 650 mg/ℓ and 56 mg/ℓ respectively, the aeration system has the capacity to effectively treat approximately 40 Mℓ/day

Secondary treatment consists of five clarifiers with a return activated sludge (RAS) pump station fitted with centrifugal pumps operating on variable speed drives. The effluent from the clarifiers is disinfected using a high concentration chlorine solution which is discharged into the effluent upstream of the chlorine contact tank.

The chlorine disinfection unit process is followed by a series of maturation ponds / lagoons. In total there are three ponds / lagoons with a total volume of 20 428 m^3 giving a total retention time of 8.2 hours for the design flow of 60 Mℓ/day.

The sludge treatment system currently has two sources of sludge produced and subsequently processed. Primary sludge withdrawn from the underflow of the primary sedimentation tanks is forwarded to a gravity sludge thickening stage before passing through a pre-fermentation process and then onto anaerobic digestion. The pre-fermentation process produces a supernatant high in volatile fatty acids (VFA's) which is returned to the liquid treatment phase and aids in denitrification ahead of the aeration basis.

The second sludge phase is the wasting of activated sludge. At Darvill WWW mixed liquor is wasted directly from the activated sludge reactor upstream of the final clarifiers. The waste mixed liquor is screened and thickened with a dissolved air flotation plant before being blended with the digested sludge and disposed of on the sludge lands adjacent to the WWTW site.

Table 8 summarizes the final effluent quality from Darvill wastewater works ex the secondary clarifiers and pre-disinfection with chlorination for the project period. As the pilot plants were run in parallel to the main plant and utilised the same feed water so it was possible to make direct comparisons between the permeate water quality of the pilot plants and the final effluent water quality of the Darvill wastewater works for the same period.

Table 8: Darvill WWW final effluent water quality

Parameter	Units	No. of Analyses	Average	Median	Minimum	Maximum	Std Dev
Conductivity	mS/m	239	76	77	42	102	12
SS	mg/l	239	25	17	4	175	84
COD	mg/l	239	47	41	20	240	30
E.Coli	CFU/100 ml	239	11055	140	8	579000	58117
Ammonia	mg/l	238	13	13	1	30	9
Nitrite	mg/l	10	2.6	0.5	0.5	20	6.2
Nitrate	mg/l	237	1.0	0.5	0.5	7.3	1.2
O&G	mg/l	10	1.2	1.2	1.2	1.6	0.1
SRP	mg/l	240	0.5	0.3	0.0	3.7	0.6

Table 9 summarizes the effluent discharge standards set by the regulating authority the Department of Water and Sanitation (DWS).

Table 9: Darvill WWW effluent discharge standards

Parameter	Limit
COD final	75 mg/ℓ
BOD final	10 mg/ℓ
NH_3 final	6 mg/ℓ
NO_3 final	15 mg/ℓ
Ortho Phosphate	1 mg/ℓ
Suspended Solids	25 mg/ℓ
pH	5.5 – 9.5

4.5 Pilot Plants

The two MBR pilot plants installed were Norit and Toray. The pilot plants were located adjacent to the existing activated sludge tanks (ASTs) on an open piece of ground. The Norit MBR pilot plant was installed and operated on a newly constructed concrete slab. The Toray pilot plant was containerised and was therefore installed on specifically designed concrete plinths. The pilot plants had easy access to the works' primary effluent, to electrical power, to discharge channels for waste sludge, to permeate and to potable water. Each MBR process component was easily accessible. The two MBR pilot plants were equipped with submersible pumps that were connected to a 20 kℓ storage tank supplied with primary effluent. The primary effluent is abstracted from the feed well to the ASTs as settled sewage and pumped via a 90 mm uPVC rising main to the 20 kℓ storage tank. The storage tank is equipped with float switches to control the supply of sewage to tank. A layout plan of the MBR pilot plants set-up is given in **Figure 6** below and **Figure 7** provides a picture of the set-up.

The sewage at this stage is locally known as settled sewage as it has already received primary treatment. The primary treatment at Darvill WWW involves screening (5 mm) and settling in the primary settling tanks, after which it is pumped to the ASTs. Although the position of the demonstration plants was convenient from an abstraction view point, a major disadvantage, which only became apparent during the study, was that the raw influent COD had been markedly reduced. The primary treatment processes was removing 30 to 40% of the influent COD and thus the influent into the demonstration plants had relatively low COD. This is thought to have impacted negatively on biomass growth during the project as MLSS could not be increased to target levels of above 10,000 mg/l. A historical record of the water quality from the inlet to the ASTs (settled sewage) is provided in **Table 10.** It is evident in **Table 10** that the average COD concentration of 251 mg/ℓ is low.

Table 10: Historical Darvill WWW settled sewage water quality (2000 – 2009)

	Units	Mean	Std Dev	Median	95th %tile	Min	Max	No. of Analyses
Alkalinity	mg $CaCO_3$/ℓ	204	58	202	275	10	822	475
COD	mg O_2/ℓ	251	186	218	496	20	2822	482
Colour	'H	27	20.52	24	49	1.00	235	151
Conductivity	mS/m	70.5	16.8	68	94	36	253	444
NH_3	mg N/ℓ	21.0	7.29	21.20	30.90	0.50	45	473
OG*	mg/ℓ	12.80	9.77	9.60	29.56	1.20	50	33
pH		7.6	0.60	7.40	8.90	6.40	9.60	482
SRP*	ug P/ℓ	3985	2705	3580	8830	170	21420	473
SS	mg/ℓ	86	39	80.00	154	4.00	332	475
TKN	mg N/ℓ	29	9.81	28.80	45.16	5.49	62	285

*Note: OG – Oil and Grease; SRP – Soluble Reactive Phosphate

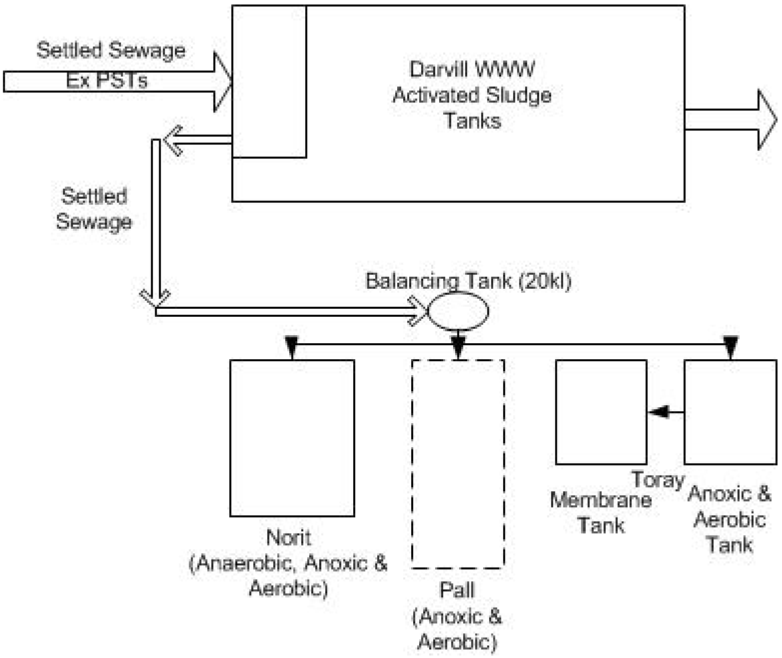

Figure 6: Plan layout of MBR Pilot Plants

Figure 7: Onsite MBR Pilot Plant Set-up

4.5.1 Norit MBR

The Norit MBR demonstration plant provided by Norit Process Technology consisted of a bioreactor and external membrane module. Settled sewage is fed into an anaerobic tank via a 0.8 mm roto-sieve drum screen using a submersible pump controlled by a programmable logic controller (PLC) to maintain a constant water level in the tank. The influent flow rate is 7.5 m^3/h. A photograph of the Norit MBR pilot plant is shown in **Figure 8**. The bioreactor (5.5 m^3) comprises three zones: the aerobic (2.7 m^3), the anoxic (1.4 m^3) and the anaerobic zones (1.4 m^3) which cater for nitrification, denitrification and phosphate removal respectively. Hydraulic balance in the bioreactor is maintained by overflow from the anaerobic to the anoxic zone and underflow from the anoxic to the aerobic zone. There are mixers in place in all the zones to ensure good suspension of solids. There is a recirculation pump from the aerobic to the anoxic zone and from the anoxic to the anaerobic zone for phosphate removal. Installed at the bottom of the aerobic zone are air diffusers. Oxygen is supplied through these diffusers via an aeration blower. The plant configuration is represented graphically by a process flow diagram in **Annexure A.**

Figure 8 Norit MBR Pilot Plant showing Drum Screen (far left)

The sludge from the aerobic zone is pumped into the external membrane for filtration. The membrane, which is three metres in height, is vertically placed and consists of 1,023 tubes of 3 mm in diameter. Sludge is fed into the membrane module at the bottom from where it is pushed up by scouring air supplied by an airlift pump, to maintain a turbulent cross flow. The air flow is controlled by a throttle valve to ensure that the air supplied corresponds to the sludge flow intake into the membrane. Too much air supply leads to a shortened retention time in the membrane as most of the sludge is blown out before filtration. Too little air supply means a loss in membrane area during filtration as the sludge collects at the bottom of the module. Permeate collects on the outside of the membrane via a suction pump. Permeate is then stored in the permeate tank and is used for backwashing Sludge from the membrane collects on the inside of the membrane and overflows back to the aerobic tank from the top of the module. The biomass (sludge) return from the membrane vessel can be configured to return to any of the three tanks. The biomass is not returned to the anaerobic tank as the return flow is highly oxygenated and would nullify the phosphorous removal process in the anaerobic tank. A filtration sequence takes seven minutes and then an automatic backwash sequence begins, lasting approximately 10 seconds. The backwash residue flows back into the aerobic zone of the bioreactor. After 10 sequences of filtration/backwashing, the membrane module is gravity drained and backwashed. The residue drained flows into the drain tank where a submerged pump discharges it back into the inlet screen.

The whole process was operated as a closed-loop system where no sludge wasting was taking place. Accumulation in the system is controlled via an overflow line in the bioreactor. All overflow lines discharge into head of works. The Norit MBR membrane module consisted of one 38 PRV external polyvinylidene fluoride (PVDF) tubular membrane module with a nominal pore size of 0.03 µm and a membrane area of 29 m^2. These external tubular membranes provide a wide-channel, non-clogging design and can be operated at high MLSS levels of up to 15,000 mg/l. Because the membrane module is located outside the bioreactor, no membrane system components are submerged in the mixed liquor. A photograph of the external membrane module is shown in **Figure 9** below. The Toray MBR plant is visible in the background with the drum screen mounted on the roof of the container. Construction of the plinths to hold the Pall Corporation 40 foot container can also be seen.

Figure 9: Norit MBR Pilot Plant showing External (Vertical) Membrane Module

4.5.2 Toray MBR

The Toray MBR pilot plant provided by CHEMIMPO (Pty) Ltd consisted of a 10 m^3 anoxic tank, a 10 m^3 aerobic tank and a 10 m^3 membrane tank which contains a submerged flat sheet membrane module. Settled sewage is fed by a submersible pump into the anoxic zone at a flow rate of 13 m^3/h. The submersible pump is controlled by a PLC to maintain a constant water level in the tank. Hydraulic balance between the anoxic and aerobic zones is maintained through an overflow. The anoxic zone is fitted with a mixer to allow for the suspension of mixed liquor solids. The aerobic zone is fitted with 10 fine bubble pipe diffusers for carrying out aeration inside the tank with air supplied by a blower. Activated sludge is pumped by a submersible pump mounted in the aerobic zone into the 10 m^3 membrane tank through a 3 mm rotating drum screen. A blower supplies air to the membrane tank coarse bubble diffusers at the bottom to allow for solids suspension inside the tank and membrane scouring. The plant configuration is represented graphically by a process flow diagram in **Annexure A.**

The flat sheet membrane module is immersed in activated sludge, and filtration occurs through an "out-to-in" mechanism whereby permeate collects on a common permeate line from the membrane sheets. The Toray immersed module TMR140-050S consists of 50 flat sheets made of PVDF with a pore size of 0.08 µm and a membrane surface area of 70 m^2. The surface area of one element is 1.4 m^2. The membrane tank can operate efficiently at MLSS concentrations of up to 13,000 mg/ℓ. Filtration is driven by a permeate suction pump that draws from the common permeate line. In filtration, the opening of the permeated water flow control valve is automatically controlled for the flow rate. The pilot operates through what is called intermittent filtration. In this type of filtration process, filtering is suspended at certain intervals whilst air diffusion continues. While filtration is suspended, air diffusing occurs in the absence of suction, enabling effective cleaning of the membrane surfaces. A recirculation pump in the membrane tank discharges into the anoxic zone in order to maintain a mixed liquor solids balance between the two tanks. Mixed liquor suspended solids wasting is only conducted when the solids concentration increases above specification and wasting is done by opening the drain valve on the membrane tank. Online probes are used to monitor operating conditions. The pilot plant is fully automated and is operated through a SCADA control system.

A summary of the demonstration plant specifications is given in **Table 11**.

Table 11: Summary of MBR pilot plant specifications

	Norit	**Toray**
Membrane Type	Tubular	Flat Sheet
Configuration	External	Submerged
Pore Size (µm)	0.03	0.08
Reactors	Anaerobic, Anoxic, Aerobic	Anoxic, Aerobic
Operational Period	54 weeks	30 weeks

4.5.3 Membrane Cleaning

Chemical cleaning of the membranes of the MBR demonstration plants was carried out in response to specific data or operational events such as:

- An increase in trans membrane pressure beyond the supplier's recommendations;
- Shut downs and restarting of the plant after an extended period, due to operational events such as pollution.

According to the supplier's recommendations, chemical cleaning is generally required every three months for the Norit membranes and every six months for the Toray membranes. However, in practice, cleaning was required more frequently. The Toray plant membranes, in particular, required cleaning far more regularly. Chemical cleaning in place (CIP) for both MBR systems involves the use of sodium hypochlorite and citric acid, for the removal of organic and inorganic fouling respectively. Cleaning can be either a maintenance clean which involves soaking in one or both chemicals for a few hours or an intense clean which involves soaking overnight.

4.6 Test Design

The pilot plant trials were divided up into the four phases (**Table 12**): Phase 1) Start-up, 2), Short-term tests, 3) Long-term tests and 4) Peak flux tests.

Table 12 Test design

Ph 1) Start-up	Ph 2) Short-term tests	Ph 3) Long-term tests	Ph 4) Peak flux tests
Start-up and technical testing, Establishment of operational routines Testing of on-line measurements of data loggers Testing of remote access internet plant control	Specific tests with a high frequency of sampling to quantify the performance parameters and verify the proof of concept. Testing of cleaning regimes e.g. CIP	Tests to identify the development of operational and treatment performance parameters over time	Tests to identify the peak flux rates of the membranes
Duration: 5 weeks	Duration:16 weeks	Duration:26 weeks	Duration: 3 weeks

4.7 Performance Parameters

Numerous analytical methods were applied during the pilot tests. A list of analytical laboratory instrumentation used is given in **Annexure B**. The resulting data will relate to both the operation of the biological reactors and the performance of the membranes. In relation to the test objectives, the following key performance parameters were quantified (**Table 13**).

Table 13 Performance parameters

Parameter	**Unit**	**Definition**
Operational		
Permeate flux	lmh	Water flux through membrane
MLSS	mg/ℓ	Concentration of suspended solids
Dissolved Oxygen (DO)	mg/ℓ	Concentration of DO
Permeability	lmh/bar	Ratio of flux to TMP
Trans Membrane pressure	mbar; bar	Immersed MBR: Static pressure - dynamic pressure. External MBR: Module Top Pressure + Module Bottom Pressure)/2
Effect of cleaning procedure	Change in permeability (K)	Improvement in K per cleaning event
Permeate Water Quality		
Particulate Removal		
Turbidity	NTU	Membrane performance measure
Suspended Solids	mg/ℓ	Membrane performance measure
Inorganic Nitrogen Removal		
Ammonia	mg/ℓ	Measure of nitrification
Nitrate	mg/ℓ	Measure of denitrification
Organics		
Chemical Oxygen Demand (COD)	mg/ℓ	Measure of biological process
Biochemical Oxygen Demand (BOD)	mg/ℓ	Measure of biological process
Removal of micro-organisms		
Total Coliforms	Log-reduction	Reduction of bacteria concentration
Coliphages	Log-reduction	Reduction of virus concentration
E.Coli	Log-reduction	Reduction of bacteria concentration

4.8 Analytical Parameters

During the course of the pilot plant testing, water quality samples were collected and analysed to assess the performance of the MBR plants. Several water quality parameters including pH, DO, MLSS, diluted sludge volume index (DSVI) and turbidity were monitored onsite. Onsite measurements were made using both portable and online instrumentation. The plant operators undertook MLSS, DSVI and ultra-violet $(UV)_{254}$ analyses in the onsite laboratory to confirm measurements from online instrumentation.

4.8.1 Automated and manual sampling and analysis

pH

The MBR plants were equipped with online pH meters (Hach Lange) which were used to measure the pH in the aeration tanks.

Turbidity

Turbidity readings for the MBR permeate were taken online using a Hach Lange Ultraturb SC turbidimeter.

Dissolved Oxygen (DO)

DO levels were measured in the MBR aeration tanks three times a week using a handheld Hach HQ40d DO meter. DO was also measured in the aeration tanks using online Hach Lange SC DO meters installed on the MBR plants.

Temperature (^{o}C)

The temperatures of the aerobic and membrane tanks of the MBR plants were monitored using in-line temperature probes. These values were periodically verified using a thermometer.

Mixed Liquor Suspended Solids (MLSS)

The suspended solids (SS) concentration was measured for the MBR aerobic tanks using an online Hach Lange Solitax SC SS meter. Grab samples were also taken on a daily basis and the MLSS analysed in the onsite laboratory as backup to the online meter.

Diluted Sludge Volume Index DSVI

Grab samples were taken on a weekly basis from the aerobic tank and analysed in the onsite laboratory by the operators. The purpose of the DSVI test is to monitor the settling characteristics of the mixed liquor.

UV_{254} (cm^{-1}) Absorption Units

Ultra Violet (UV_{254}) tests were performed on the permeate water using a spectrophotometer to assess the need for enhanced coagulation in future downstream treatment processes.

4.8.2 Laboratory water quality analysis

The remaining water quality parameters were measured offsite in the laboratory at Umgeni Water's Head Office. Water quality samples were sent on a daily basis, on weekdays. All water quality samples were collected as grab samples using sample containers provided from Umgeni Water laboratory services. All samples were transported to the lab in a cooler at recommended temperature and were processed within the allowable holding period. Before collecting samples, all sampling ports were flushed for a few seconds. The samples for microbiology analysis were collected after the sampling ports were properly flushed. The list of determinants chosen for analysis was based on typical constituents found in wastewater (Metcalf and Eddy, 2011) and had to be limited due to laboratory costs. The detection limits for some of the determinants, as set at Umgeni Water laboratory, are provided in **Table 14**.

Table 14 Umgeni Water laboratory detection limits

Parameter	Detection Limit	Units
Turbidity	0.2	NTU
Total Phosphorous (TP)	0.5	mg/ℓ
Suspended Solids (SS)	4.0	mg/ℓ
Total Kjeldahl Nitrogen (TKN)	3.0	mg/ℓ
Biochemical Oxygen Demand (BOD)	1.0	mg/ℓ
Chemical Oxygen Demand (COD)	20	mg/ℓ
Total Organic Carbon (TOC)	0.7	mg/ℓ
Ammonia-N	0.5	mg/ℓ-N
Nitrate-N	0.5	mg/ℓ-N
Nitrite-N	0.5	mg/ℓ-N
Orthophosphate-P	0.1	mg/ℓ-P
Total Coliforms	0	CFU/100 mℓ
Faecal Coliforms	0	CFU/100 mℓ
Total Coliphages	0	PFU/100 mℓ

4.9 Data Analysis Techniques

The data was analysed using the following statistical techniques:-

- Simple statistical measures were used to determine the average, median, maximum, minimum, 95th percentile and standard deviation of each determinant in the permeate water quality. These allowed direct comparison of the concentrations and removal/reduction efficiency of different determinands over the test period for the two MBR plants and the Darvill WWW.
- The F-test was used to compare variability in the processes.
- A student t-test for the MBR permeate and Darvill final effluent data (MBR Pilot-vs. full-scale Darvill WWW) was conducted. Values of $p < 0.05$ were considered to indicate statistical significance.
- A reliability analysis was undertaken to determine the performance reliability of each MBR treatment process, in other words the percentage compliance in removing determinands to a specified standard.

4.9.1 Statistical comparison of sample means and variance

F-test

[5]The F-test allows any two independent variances, regardless of the number of degrees of freedom (d.f.) in each, to be compared under the null hypothesis that they are sample variances from populations with a common variance. The F-test null hypothesis H_o: $\mu_1 = \mu_2$ assumes that the populations are normally distributed and have a common but unknown variance.

The F-test takes two randomly selected samples from two normal populations X and Y, with m and n observations respectively, then the variable

$$F = \frac{S_X^2}{S_Y^2} \qquad (15)$$

follows the F distribution with (m-1) and (n-1) d.f. provided the variances of the two normal populations are equal. In other words, the Null Hypothesis is H_o is $\sigma^2_X = \sigma^2_Y$ and the alternative Hypothesis is that, H_1 is $\sigma^2_X \neq \sigma^2_Y$

The formula used for sample variance is,

$$S_X^2 = \sum \frac{(X_i - \bar{X})^2}{m-1} \qquad (16)$$

$$S_Y^2 = \sum \frac{(Y_i - \bar{Y})^2}{n-1} \qquad (17)$$

Where,

S^2 = Variance

X or Y = Values given in a set of data

$\bar{X}$ or $\bar{Y}$ = Mean of the data

m or n = Total number of values

The calculated F value is compared with the tabular F value for the requisite degrees of freedom for the numerator and denominator to decide whether to accept the null hypothesis of no difference between population variances or the alternative hypothesis of a difference. If the two population variances are in fact equal, the F value given in Equation 15 should be close to 1, whereas if they are different, the F value

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[5] Data analysis techniques were performed using built in or custom Microsoft Excel functions.

should be different from 1. The greater the difference between the two variances is, the larger the F value will be.

Student t-Test

The independent-samples t-test evaluates the difference between the means of two independent or unrelated groups. That is, we evaluate whether the means for two independent groups are significantly different from each other.

The assumptions underlying the t-test are that:-

- X follows a normal distribution with mean μ and variance σ^2
- The two populations being compared should have the same variance
- The data used to carry out the t-test should be sampled independently from the two populations being compared

The mean of the t distribution, like the standard normal distribution, is zero, but its variance is k / (k-2). Therefore, the variance of the t-distribution is defined for d.f. greater than 2. As k increases, the variance of the t-distribution approaches the variance of the standard normal distribution, namely, 1. If k = 30, the variance becomes 30/28 = 1.07 which is not much greater than 1. Hence sample sizes of 30 and above can be assumed to be normally distributed.

The null hypothesis is designated as H_0 and the alternative hypothesis is designated as H_1. The null hypothesis, H_0, specifies the value of the parameter to be tested, in this case, the population mean μ (unknown) is equal to some hypothesized value, μ_0.

Thus, for two-tailed tests the null hypothesis is expressed as: $H_o: \mu_1 = \mu_2$;

and the alternative Hypothesis is: $H_1: \mu_1 \neq \mu_2$

If the null hypothesis is rejected then the alternative hypothesis is accepted.

The next step is to choose the level of significance (α) at which to conduct the test. It is common to work with 5 percent or 1 percent significance levels (Gujarati, 1999). The t-value is calculated using Equation 18 below.

The formula used for calculating the t value is,

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}} \qquad (18)$$

Where,

$\bar{x}_1$= Mean of first set of values

$\bar{x}_2$= Mean of second set of values

S_1 = Standard deviation of first set of values

S_2 = Standard deviation of second set of values

n_1 = Total number of values in first set

n_2 = Total number of values in second set.

It is now required to define the dividing line between the acceptance and rejection regions by calculating t-critical. Once the critical value has been determined then a decision to accept or reject the null hypothesis can be made. When t-calculated is greater than t-critical the H_0 is rejected and we conclude the two means are significantly different.

4.9.2 Reliability analysis

Theoretical background

The reliability of a system is defined by Chorafas (1960) as the probability of achieving adequate performance for a specific period of time under certain conditions. With reference to this study, reliability can be defined more specifically as the percentage of time measured effluent concentrations comply with a certain discharge standard or performance target. Niku et al. (1979) developed a method of determining the performance reliability of a system or individual unit process within a treatment system using the coefficient of reliability (COR).

Because of the variable nature of the influent quality and quantity, the inherent variability in wastewater treatment processes and mechanical reliability there is always a risk that set performance targets may not be achieved. The risk of failure that is acceptable depends of the engineer's design criteria. Avoiding failure completely may require increased capital investment that is not deemed necessary for the intended purpose. The treatment process is therefore designed to produce an average concentration below the required discharged standards. As described by Metcalf and Eddy (2004) a statistical approach involving the coefficient of reliability can be used to estimate the design mean value needed to meet a set standard.

The probability of failure is extremely sensitive to the distribution function of the effluent concentration. Once this distribution is known, an expression may be found to define the fraction of time that a given concentration has been exceeded in the past and, consequently, the future performance of the plant can be predicted (Dean and Forsythe, 1976a). As reported by a number of studies (Dean and Forsythe, 1976, Niku et al. (1979) and Charles et al. (2005) the log-normal distribution gives the best overall fit to most wastewater treatment works effluent concentration values. The COR developed by Niku etal. (1979) assumes the log-normality of the data and should only be applied if this holds true.

Method of Analysis

Test for Data Distribution

The method developed by Niku et al. (1979) required that the data be tested for normality first. This was done using the Kolmogorov-Smirnov test, which transforms the data to a logarithmic value to test the type of distribution. The log-transformed data was observed to be normally distributed for some variables (Refer to Norit Electrical Conductivity (EC) plot in **Annexure D**). Variables that were not log-normally distributed were assumed to be empirically distributed.

Percentage Compliance

The analysis can be taken a step further and the expected level of compliance with the discharge standard is calculated using an equation derived by Niku etal, (1979), that is,

$$Z_{1-\alpha} = \frac{\ln X_S - \left[\ln m_x \;-\; \frac{1}{2}\ \ln(CV^2+1)\right]}{\sqrt{\ln(CV^2+1}} \qquad (19)$$

Where:

m_x = mean effluent concentration (mg/ℓ)

CV = coefficient of variance (standard deviation divided by the mean)

X_s = water quality standard to be achieved

$Z_{1-\alpha}$ = standardized normal variate (obtained from the standard normal variate tables) corresponding to the probability of no exceedance at a confidence threshold of (1-α)

α = significance level

After the calculations of $Z_{1-\alpha}$ the corresponding value of 1-α can be obtained from the standard normal variate tables thus providing an expected level of compliance with the applicable discharge standard.

Determination of Design Mean

The coefficient of reliability (COR) is calculated using the following equation (Niku etal, 1979)

$$\text{COR} = \sqrt{CV^2 + 1} \text{ x } \exp\{-Z_{1-\alpha} \sqrt{\ln(CV^2 + 1.)}\} \qquad (20)$$

Where:

CV = coefficient of variance (standard deviation divided by the mean)

$Z_{1-\alpha}$ = standardized normal variate (obtained from the standard normal variate tables) corresponding to the probability of no exceedance at a confidence threshold of (1-α)

α = significance level

From the COR obtained, it is possible to determine the design concentrations that would be required to achieve the discharge standards (Oliveira and Von Sperling, 2008).

The COR relates the mean effluent concentration to the standard to be achieved, on a probability basis. The mean value (m_x) may be obtained by the relationship:

$m_x = (\text{COR})X_s$

Where m_x = mean effluent concentration (design or operational value)

X_s = specified discharge standard

COR = coefficient of reliability

4.9 Cost Estimate

A high level cost estimate was undertaken to establish the capital and operating cost of installing MBR at Darvill WWW. This was compared to the capital and operating cost of conventional activated sludge treatment at Darvill WWW, if the works was upgraded. Cost estimates were based on a literature review and from discussions with engineering consultants, contractors and MBR vendors. As this cost estimate is not part of the research objectives of the study it is included in **Annexure G** for information purposes only.

CHAPTER 5: PERFORMANCE EVALUATION

5 PERFORMANCE EVALUATION

5.1 Operational History and Parameters for the MBR Pilot Plants

Umgeni Water had no experience with MBR plants and a period of transition was therefore required for training and to become accustomed to operating the pilot plants. The MBR pilot plant suppliers provided engineers to assist with the start-up and operation of the plants and they provided training for the operators. A number of start-up problems were experienced which made the running the plants for the first few months quite onerous and made it difficult to achieve stable operating conditions. Stable operating conditions are essential for achieving representative and repeatable performance results. Stable operation was tracked by measuring the dissolved oxygen (DO) and mixed liquor suspended solids concentration (MLSS) in the bioreactor. A summary of the operating history is given in this section, highlighting the operational problems experienced on both plants and the DO and MLSS concentrations with time are represented graphically.

5.1.1 Toray MBR operating history

The pilot plant was originally supplied with only a membrane tank and no biological nutrient removal (BNR) treatment processes. Umgeni Water therefore requested Toray add additional aerobic and anoxic tanks to the plant, at the very minimum. An anaerobic tank would also have been preferable, but the additional cost could not be accommodated. Toray engaged the services of a South African process engineering firm Keyplan (Pty) Ltd to manufacture the containerized bioreactor and they completed this work within three months. Another two months passed before the plant was fully operational, at which point the Norit plant had been operating for 24 weeks. Graphically the operating history of the Toray plant is thus represented from Week 25 onwards.

The plant was operated for a month but was offline for the second month because of an instrumentation failure. At the end of week 29 the aerobic tank water level probe failed, resulting in no raw wastewater influent entering the bioreactor overnight and thus the plant emptied itself. Reseeding was normally done using an old diaphragm pump borrowed from the Darvill WWW, but this pump broke down. A new submersible pump and pipe had to be procured and this took just over a week at which point the plant was reseeded. Later in the month over the Christmas holidays an industrial effluent discharge into the sewer system contaminated the feed to the bioreactor and killed all the sludge reducing the MLSS concentration to less than <1000 mg/l. The plant had to be completely drained and reseeded. Normal operation resumed in Week 34. The plant was operated without major incident for the next two months until the membrane tank aeration blower failed in Week 44. The blower had to be removed and repaired and thus the plant was offline for a week. After this failure the plant has operated consistently through to the end of the plant trials.

5.1.1.1 Toray MBR operating parameters

The Toray MBR plant was operated to achieve nitrification and denitrification. Significant removal of phosphorous was not expected because of the lack of an anaerobic zone. The system was initially seeded with sludge from the Darvill WWW Activated Sludge Tanks (ASTs). The concentration of sludge from the Darvill ASTs is in the 3500–4500 mg/ℓ range. The concentration of the MLSS in the Toray bioreactor did not increase with operation despite no sludge wasting taking place. The reason for this could not be explained but was impacted on by a number of operational problems that resulted in plant downtime. These problems included mechanical and instrument malfunctions on the plant as well as pollution incidents that required regular reseeding of the MBR system.

Another factor that may have inhibited biomass growth in the bioreactor is the low influent COD and high COD/BOD ratio. The median influent COD concentration was only 261 mg/ℓ and the average COD/BOD ratio was 7. A COD/BOD ratio of >6 is a rule of thumb that suggests that the influent is not readily biodegradable. **Figure 10** presents the MLSS concentrations in the aerobic tank of the Toray MBR system. It is evident that prior to week 48 the MLSS concentration was generally below 5000 mg/ℓ and could not be maintained beyond this concentration for any period of time. Experimentally this was not ideal as the study objective was to test the membranes at high (>10 000 mg/ℓ) MLSS concentrations. In Week 48 a decision was made to seed the Toray MBR system with return activated sludge (RAS) which has a MLSS concentration in the 7000 –8000 mg/ℓ range. The MLSS remained above 10 000 mg/ℓ from then on and with occasional reseeding with RAS was maintained at the target concentration of 10 000–15 000 mg/ℓ.

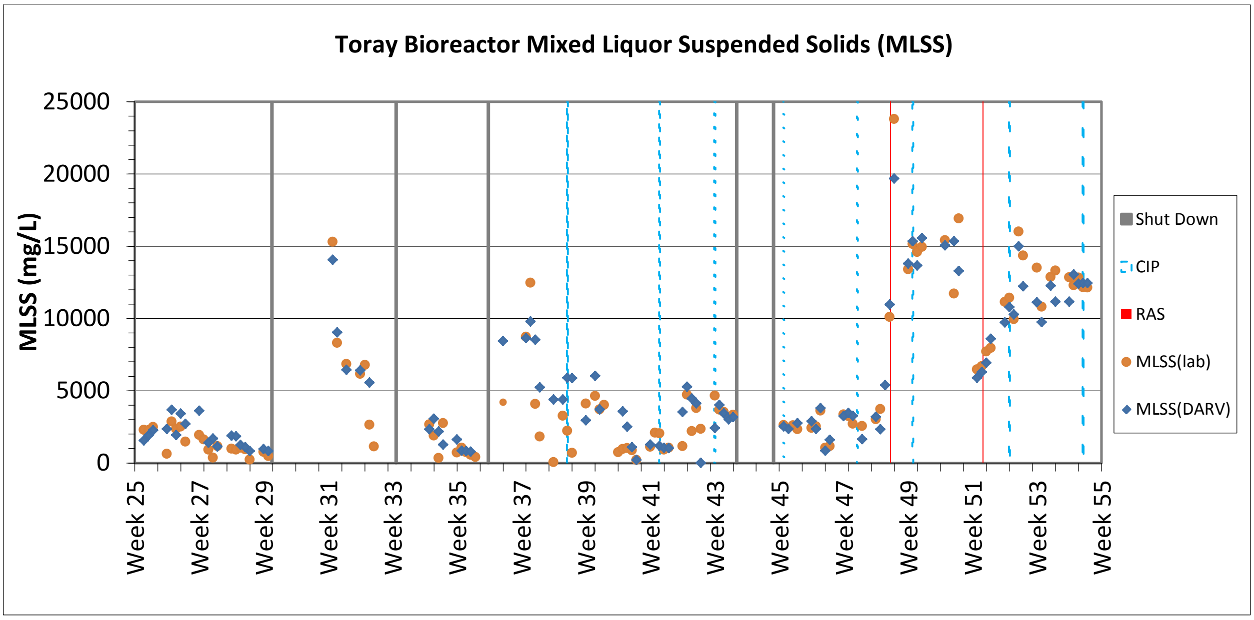

Figure 10: Toray Bioreactor MLSS Concentration

The fact that the MLSS concentration could not be maintained at the required level (> 10 000 mg/ℓ) is a short-coming of the research that was unfortunately beyond the control of the investigator. The fact that both MBRs were operated in parallel, and thus experienced the same MLSS concentrations throughout the trail period, could be a mitigating factor, ensuring that the performance comparison is still valid.

The DO levels in the aerobic tank were attempted to be maintained between 1–2 mg/ℓ. **Figure 11** shows the DO concentrations for the Toray aerobic tank. As presented in the graph the DO concentrations varied significantly in the Toray aerobic tank from near zero to as high as 8 mg/ℓ. Despite many attempts to regulate the variable speed drive (VSD) aerobic tank blower the DO concentrations could not be maintained within the target range of 1–2 mg/ℓ. This led to an over oxygenated aerobic zone. The average DO in the bioreactor was 2.5 mg/ℓ with a standard deviation of 2.2 mg/ℓ. A number of consequences may have resulted from the DO not being within the require range.

Nitrifying bacteria in the bioreactor aerobic zone require sufficient DO to convert ammonia to nitrate, and have to compete with the more active aerobic bacteria present in this zone for whatever DO is available. If the DO is insufficient, i.e. DO < 1.5 mg/ℓ due to under-aeration, then the activity of the nitrifying bacteria is reduced and nitrification could be inhibited. Conversely, with over-aeration the anoxic zone can become partially aerobic. An internal recycle saturated in DO, as was the case with the Toray MBR, could impact denitrification because the bacteria will use free oxygen (DO) rather than chemically bound oxygen attached to the nitrate ion (NO_3). Accordingly, the impact of the poor DO control in the Toray MBR is that the efficiency of the Toray MBR to remove nitrogen cannot be concluded from this investigation.

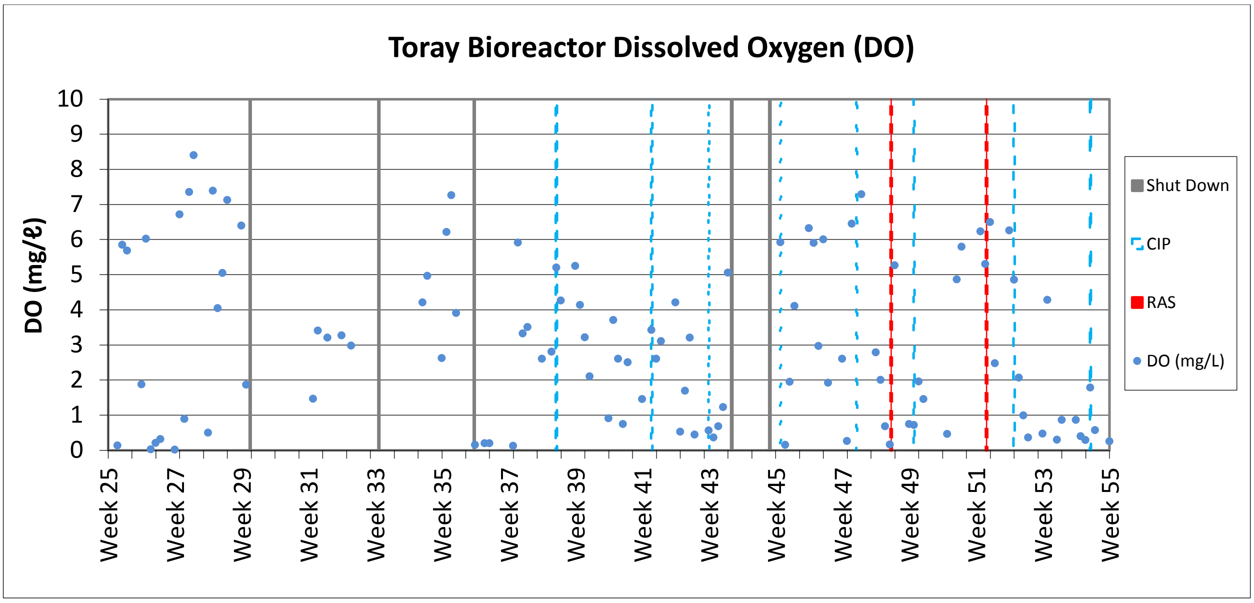

Figure 11: Toray Aerobic Tank DO Concentration

The trans membrane pressure (TMP) operating range for the Toray plant is between -30 to -130 mbar and the maximum TMP is -180 mbar at which point an alarm will stop the plant.

5.1.2 Norit MBR operating history

The system was initially seeded with Activated Sludge (AS) from the nearby Darvill WWW aerobic basin. The first month's operation was problematic with a number of stoppages. This was partly due to the steep learning curve for the operators, but also as a result of disruptive random incidents such as power failures. The situation did not improve in the following weeks, with a host of breakdowns and operational problems resulting in the plant being off-line for most of the month. The pilot was then operated for four consecutive months from Week 7 to Week 27, but not without problems, with many interruptions to operation taking place. A large proportion of these were due to SCADA faults that resulted in the plant tripping on a regular basis. The SCADA issues had to be fixed remotely by the Norit engineers, which was time consuming. The pilot plant operators and the Norit engineers were not available at night so any plant shut down could not be attended to timeously. Overnight shutdowns resulted in time consuming delays getting the plant up and running again.

In Week 28 the plant was shut down completely as there was a PLC failure that required new components that needed to be imported from Holland. Once the components had arrived and been installed the plant was unsuccessfully restarted in Week 31. In Week 35 the plant was restarted and despite on-going minor problems was operational, running until the peak tests were run in Week 54.

5.1.2.1 Norit MBR operating parameters

The Norit MBR plant was designed to operate with anoxic and aerobic tanks to achieve nitrification and denitrification. A plate was manufactured and installed in the anoxic tank in an attempt to achieve phosphorous removal by creating an anaerobic zone. The system was initially seeded with sludge from the Darvill WWW activated sludge tanks (AST). The concentration of sludge from the Darvill ASTs is in the 3500–4500 mg/l range, but the MLSS concentrations remained below 4000 mg/l in the bioreactor during the start-up period. The concentration of the MLSS in the Norit bioreactor did not increase with operation despite no sludge wasting taking place. No apparent reason for this could be established but it was thought to be because of the low COD/BOD ratios in the raw water influent and a lack of biodegradable COD providing insufficient food for effective biomass growth. The MLSS concentration is represented graphically for the Norit pilot plant in **Figure 12**. The MLSS concentration remained consistently low throughout the operation of the plant. Only when the bioreactor was seeded with RAS did the MLSS concentration approach and exceed 10 000 mg/l, but even then the higher MLSS concentrations could not be maintained for any length of time.

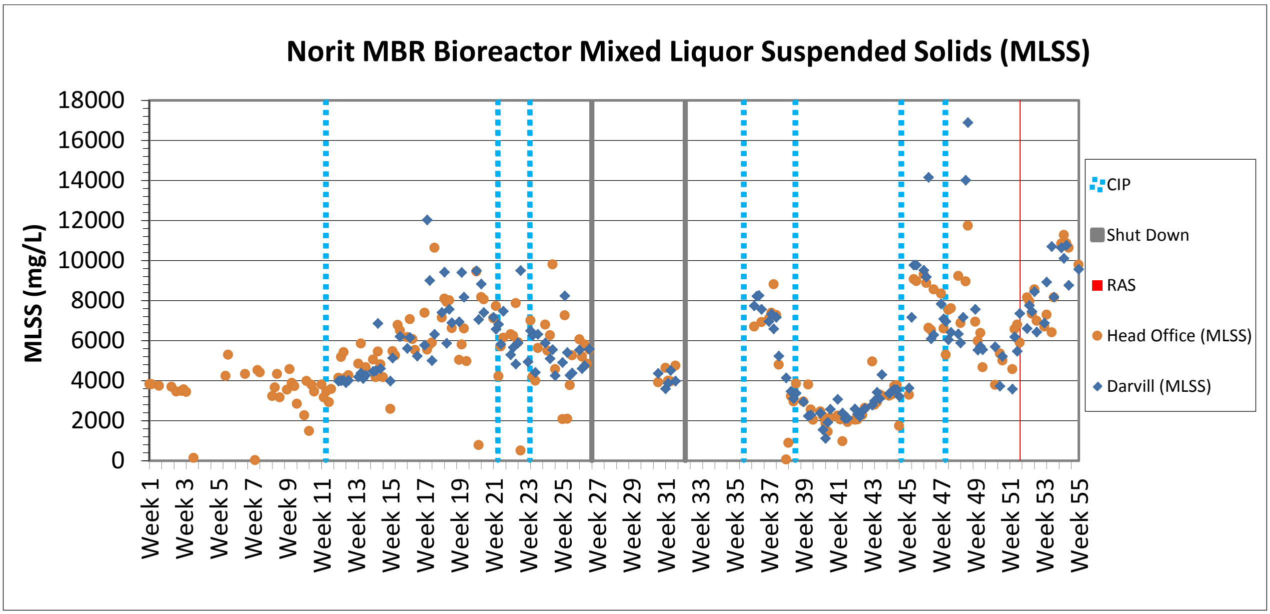

Figure 12: Norit Bioreactor MLSS Concentration

The DO levels in the aerobic tank were attempted to be maintained between 1–2 mg/l. Keeping the DO concentration within the desired range was difficult to achieve as can be seen by the variation in DO levels presented in **Figure 13**. DO control was however more successful than with the Toray system as the average DO concentration achieved was 2.1 mg/ℓ with a standard deviation of 1.2 mg/ℓ. In comparison, the Toray MBR average DO was 2.5 mg/ℓ with a standard deviation of 2.2 mg/ℓ. Great variability was therefore evident in the Toray MBR.

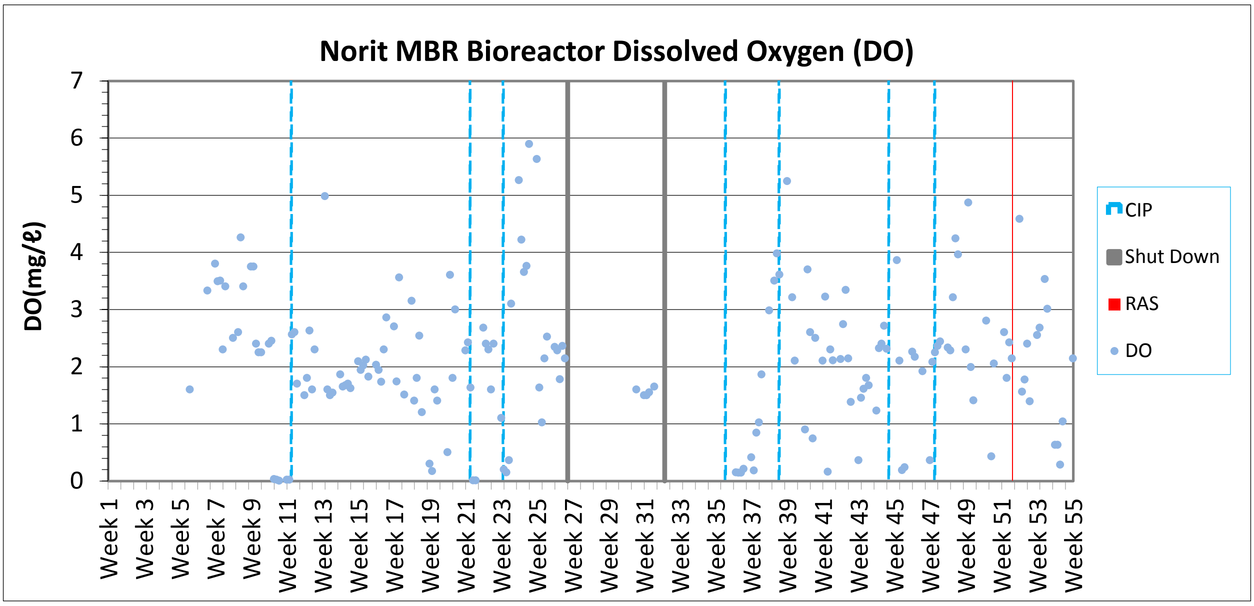

Figure 13 Norit Aerobic Tank DO Concentration

The TMP operating range for the Norit plant is between 0.1 to 0.4 bar and the maximum TMP is 0.5 bar at which point an alarm will stop the plant.

5.2 Membrane Performance Assessment

5.2.1 Toray membrane operational performance record

After the Toray MBR was seeded with sludge from the Darvill Activated Sludge Tanks (ASTs) the plant was initially operated at low fluxes (7 lmh) at the instruction of the suppliers. This was done to allow the acclimation of the membranes and to prevent possible fouling of the membranes. The operating objective over the first few months was to allow the MLSS concentration to increase to the target concentrations of 10 000–13 000 mg/ℓ. Once this was achieved the flux rate would be increased until a sustainable flux rate could be established. The TMP and flux data for the Toray MBR system are presented in **Figure 14** as well the CIPs, plant shutdowns and seeding events. The flux and permeability data are presented in **Figure 15.**

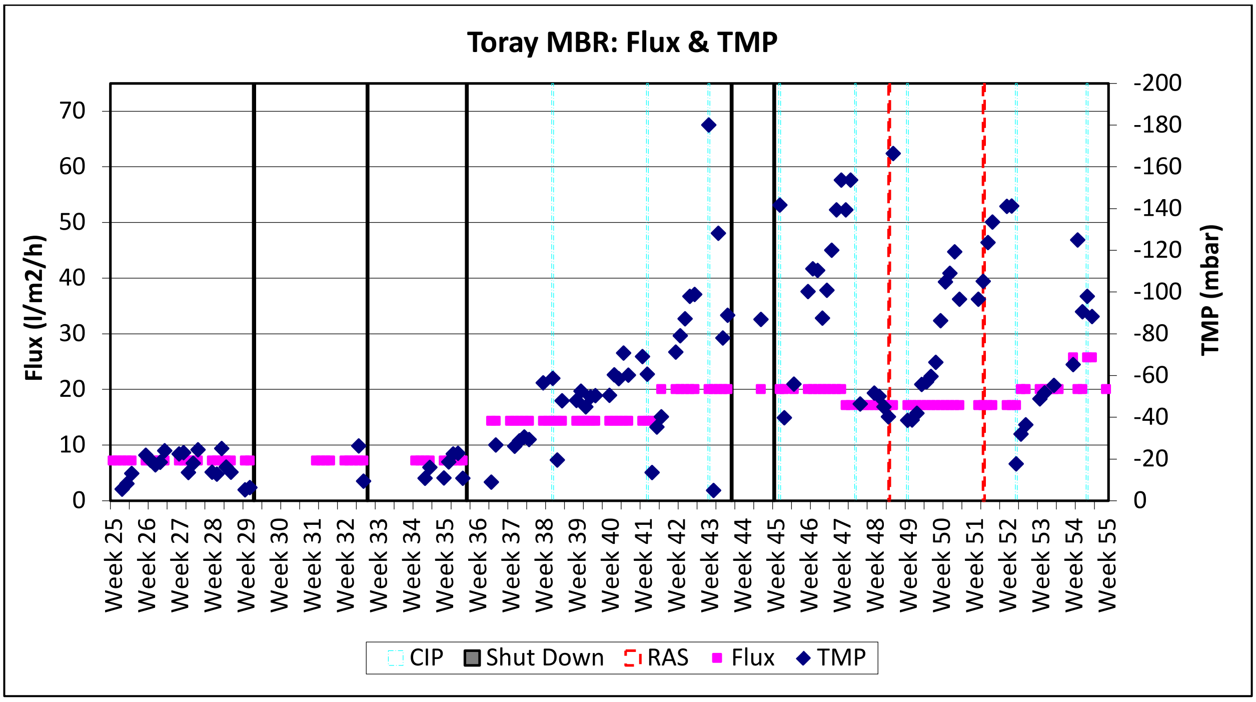

Figure 14: Toray MBR Flux and TMP[6]

As shown in **Figure 14**, the rate at which TMP increased with respect to time steadily increased as operating flux increased. This data suggests that operation at higher fluxes caused a significant increase in membrane fouling.

A similar situation is depicted in **Figure 15.** The permeability remained fairly constant from Week 25 to Week 35 when operating at a low flux (7 lmh). A gradual drop in permeability is evident from Week 36 to Week 41 when operating at a higher flux rate of 15 lmh. In general the permeability recovers well following

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[6] The negative TMP values are a Toray convention and represent t pressure difference and can be positive or negative. For submerged membranes where the permeation is done by suction it is typically negative.

a CIP, but returns to levels of around 200 lmh/mbar after 3 to 4 weeks, showing the impact of fouling on membrane performance.

A detailed operating record for the Toray and Norit MBRs is provided in **Annexure E** and the relative performance the MBR pilot plants is discussed from an operator perspective in **Annexure F**.

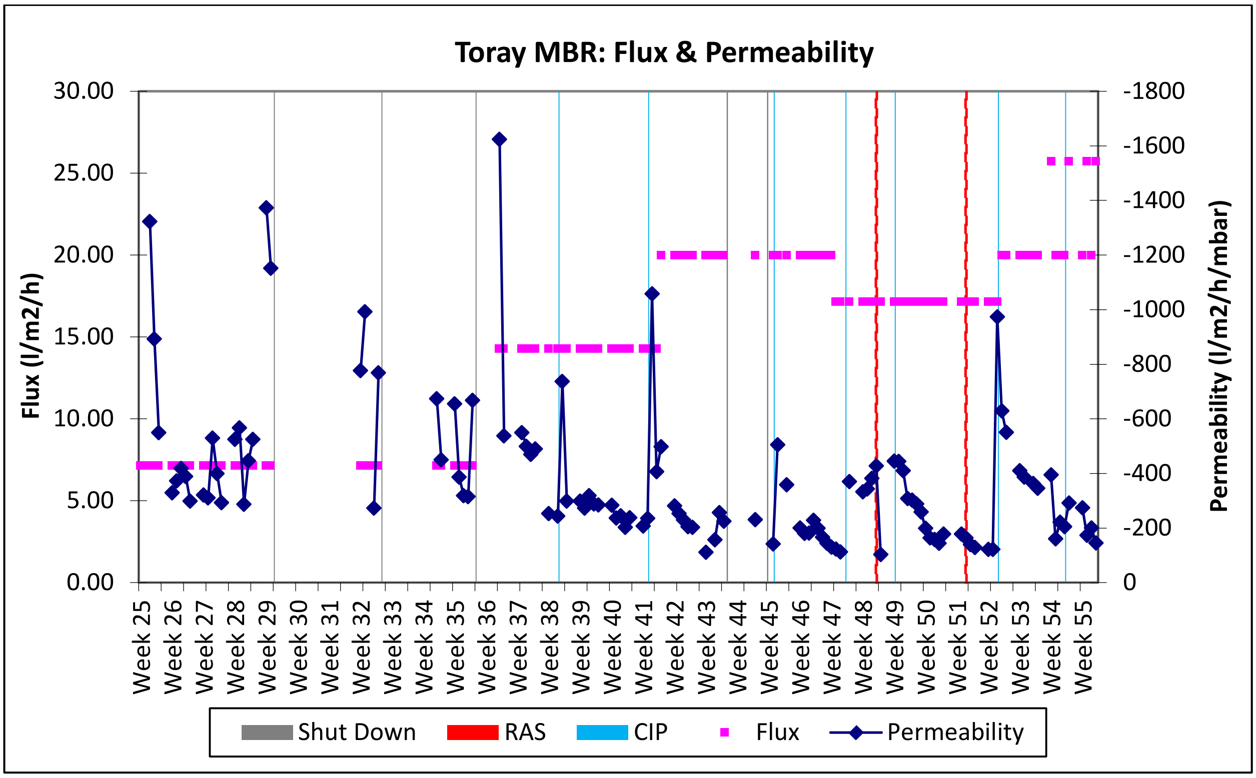

Figure 15: Toray MBR Flux and Permeability

5.2.1.1 Toray membrane operational performance evaluation

The evaluation of the operational parameters is focused on selected periods of the study. The periods were selected on the following criteria:

- Continuous operation: the plant was in duty operation without disturbances for a period of five days or more.
- MLSS range: as the membranes are designed to operate at high MLSS concentration (>10000 mg/ℓ), the operational periods with low MLSS values are not applicable.
- Stable biological process: the stability of the on-going biological processes is essential to have the required sludge filterability. Sludge adaptation periods, rapidly changing MLSS concentrations, breakthrough events of toxic industrial streams all result in general changes in the sludge filterability.

The applied cleaning conditions were different during the operation of the plant based on the actual fouling situation. The CIPs were sometimes initiated based on a programmed TMP trigger. The terminal TMP of the membranes is -200 mbar. If the TMP reached the -180 mbar level the PLC sent a warning signal, and at -200 mbar the auto operation is stopped with an alarm signal.

The applied CIP was very efficient at all cleaning events. The lost permeability was restored by the CIP to the initial value. No residual fouling was experienced during the study operational period. As the results of the short, 2-3 hour long CIPs were as good as the results of the overnight CIPs, it can be stated that the duration of the cleaning had no major effect in the cleaning results. An estimate of the impact of the CIPs is given in **Table 15** and a summary in **Table 16**.

Table 15 Toray MBR cleaning in place results

Date of CIP	TMP (before) mbar	TMP (after) mbar	Permeability (before) lmh/bar	Permeability (after) lmh/bar
Week 38	-58.6	-19.4	244	736
Week 41	-60.6	-13.5	236	1058
Week 43	-180	-4.8	111	1166
Week 45	-145.5	-39.6	141	505
Week 47	-153.5	-46.3	111	370
Week 49	-166.3	-38.6	103	445
Week 52	-141.1	-17.6	121	974
Mean	-128.8	-25.7	152	750

Table 16: Toray MBR cleaning in place summary

Cleaning Parameters	Values
TMP before CIPs (mean)	-129 mbar
Permeability before CIPs (mean)	152 lmh/bar
TMP after the CIPs (mean)	- 26 mbar
Permeability after the CIPs (mean)	750 lmh/bar

Based on the above experiences it can be seen that the CIPs are resulting in an average TMP drop of 103 mbar. The cleaning criteria can therefore be set as: - **100 mbar TMP increase requires a CIP**

This means that a CIP is required only if the TMP increases from its initial value (after previous cleaning) by 100 mbar. Similarly to avoid low permeability operations (excessive fouling danger, operational clearance) an intensive CIP has to be performed if the permeability of the membrane drops under 150 lmh/bar.

Based on the above criteria the following operational periods were evaluated to determine the membrane filtration design flux rates. The cleaning interval per period was calculated based on the potential for the

TMP to exceed the 100 mbar operating criteria. For example, during Week 36 – 37 the fouling rate was 2.3 mbar/day and therefore at this flux rate and operating conditions a cleaning would be required after 43 days. A summary of the tested flux rates is given in **Table 17**.

Table 17: Toray MBR tested flux rates

No	Description	Start	End	No. of online days	Inst. Permeate flow m^3/h	Inst. Flux (lmh)	Net Flux (lmh)	Initial TMP (mbar)	End TMP (mbar)	TMP loss mbar/d	Cleaning interval days	Average MLSS mg/l
1	14 lmh, high MLSS	Week 36	Week 37	13	1	14	13	-26	-56	2.3	43	8978
2	14 lmh, low MLSS	Week 37	Week 41	19	1	14	13	-47	-93	0.8	119	3000
3	20 lmh, low MLSS	Week 45	Week 47	15	1.4	20	18	-39.6	-161	8.1	12	2655
4	17 lmh, rising MLSS	Week 47	Week 48	6	1.2	17	15	-46	-150	17.3	6	1500 to-15000
5	17 lmh, high MLSS	Week 49	Week 51	14	1.2	17	15	-38.5	-108	7.0	14	14800
6	17 lmh, middle MLSS	Week 51	Week 52	6	1.2	17	15	-99.6	-140	6.7	15	7885
7	20 lmh, high MLSS,9/11	Week 52	Week 53	8	1.4	20	16	-30	-55	3.1	32	12148
8	20 lmh, high MLSS,9/10	Week 53	Week 54	5	1.4	20	18	-55	-65	2.0	50	12665
9	Merge of periods 7 & 8	Week 52	Week 54	13	1.4	20	18	-30	-65	2.7	37	12954

Based on the filtration rates tested, the design flux rates generally used for municipal wastewater by Toray are not applicable at Darvill WWW. The frequent CIPs required suggest that the Darvill raw wastewater influent is not a normal municipal wastewater. As it is known the Darvill influent has an industrial component of about 10% the results would appear to indicate that this is having a marked impact on the performance of the membranes, resulting in fouling. Industrial pollution incidents during the study period which killed the biomass in the bioreactor and caused a rapid rise in TMP confirm this.

The predicted average daily flux rate is 17 lmh and the predicted cleaning frequency with average daily flux is 4-5 weeks/cleaning.

5.2.2 Norit membrane operational performance record

The flux data is plotted against TMP and permeability in **Figures 16** and **Figure 17** respectively for the Norit MBR system.

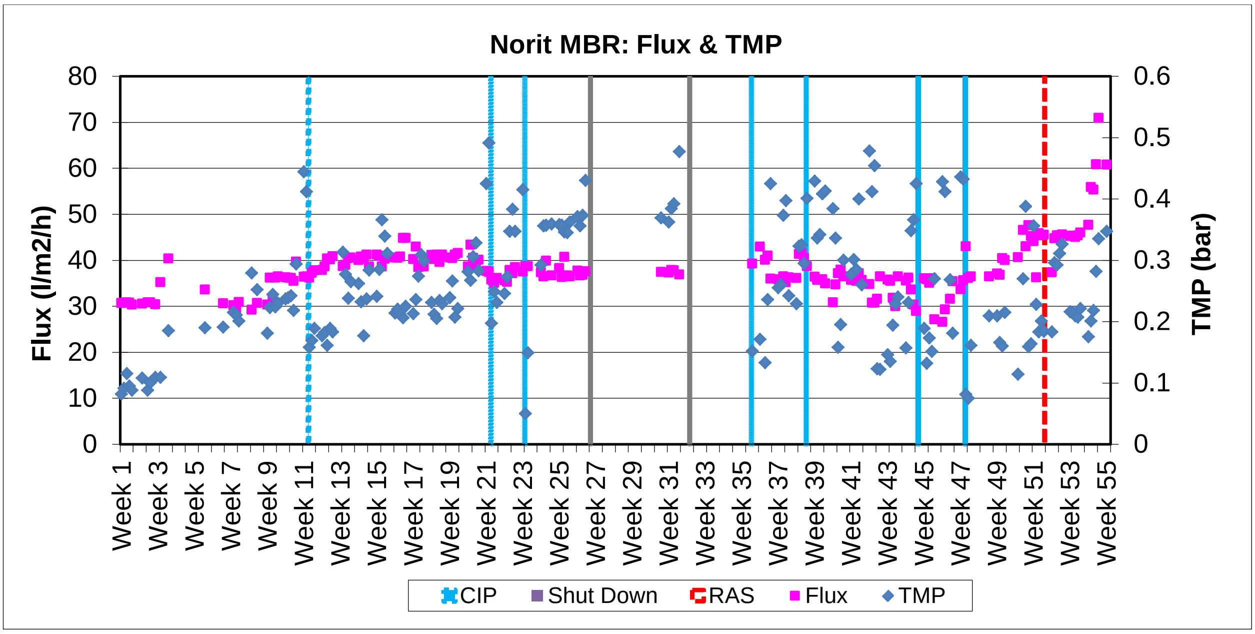

Figure 16: Norit MBR Flux and TMP

As shown in **Figure 16**, the rate at which the TMP increases appears erratic rather than as a response to the operating flux being increased. In fact it is evident that at higher MLSS concentrations towards the end of the operating period the TMP becomes relatively stable. This data suggests that to some degree the increases in TMP were as a response to operational issues. This was indeed the case where pollution incidences occurred, but was also the experience of the operators when faced with other issues such as mechanical failure. The continued malfunction of a critical operating component such as the membrane (airlift) blower caused numerous shut downs, but may also have reduced the effectiveness of scouring and thus increased the fouling potential.

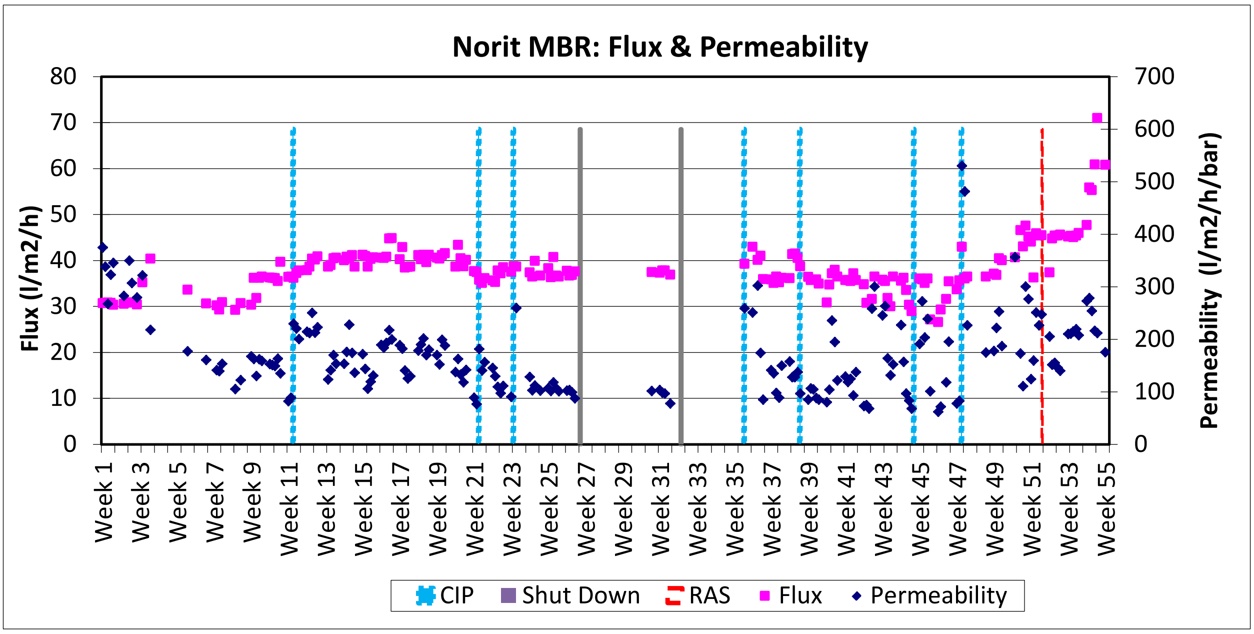

Figure 17: Norit MBR Flux and Permeability

As shown in **Figure 17**, the permeability dropped with time from Week 1 to Week 27 when operation was suspended temporarily. From week 35 onwards the permeability decreased with increases in flux as expected. The unexpected performance occurs towards the end of the tests when the MLSS concentrations were at there highest and approaching the Norit design MLSS concentration of >10000 mg/ℓ. The permeability can be seen to even improve at this juncture even though the flux rates where increasing. It is proposed that the improvement in performance is a result of the improved filterability associated with a more stable and concentrated biomass.

5.2.2.1 Norit membrane operational performance evaluation

The evaluation of the operational parameters is focused on selected periods of the study. The periods were selected on the following criteria:

- Continuous operation: the plant was in duty operation without disturbances for a period of five days or more.
- MLSS range: as the membranes are designed to operate at high MLSS concentration (>10000 mg/ℓ), the operational periods with low MLSS vales are not applicable.
- Stable biological process: the stability of the on-going biological processes is essential to have the required sludge filterability. Sludge adaptation periods, rapidly changing MLSS concentrations, breakthrough events of toxic industrial streams all result in general changes in the sludge filterability.

High MLSS above 10000 mg/ℓ were never able to be obtained without using RAS to spike the bioreactor and even then the MLSS would drop fairly rapidly. It was therefore necessary to use the most stable plant operating conditions as a guide to evaluating the membrane performance. In the last month of operation the MLSS was maintained above 7000 mg/ℓ.

The lost permeability was restored to the membranes following a CIP. An estimate of the impact of the CIPs is given in **Table 18** and a summary in **Table 19**.

Table 18: Norit cleaning in place results

Date of CIP	TMP (before) bar	TMP (after) bar	Permeability (before) lmh/bar	Permeability (after) lmh/bar
Week 11	0.412	0.158	88.36	229.15
Week 21	0.491	0.197	76.26	181.09
Week 23	0.415	0.05	90.40	259.31
Week 42	0.454	0.123	67.67	257.69
Week 44	0.425	0.189	68.05	190.97
Week 47	0.432	0.081	82.45	530.07
Mean	0.438	0.133	78.87	274.71

Table 19: Norit cleaning in place results summary

Cleaning Parameters	Values
TMP before CIPs (mean)	0.438 bar
Permeability before CIPs (mean)	79 lmh/bar
TMP after the CIPs (mean)	0.133 bar
Permeability after the CIPs (mean)	275 lmh/bar

Based on the above experiences it can be seen that the CIPs are resulting in and average TMP drop of 0.305 bar. The cleaning criteria can therefore be set as:-**0.3 bar TMP increase requires a CIP**

This means that a CIP is required only if the TMP increases from its initial value (after previous cleaning) by 0.3 bar. Similarly to avoid low permeability operations (excessive fouling danger, operational clearance) an intensive CIP has to be performed if the permeability of the membrane drops under 80 lmh/bar.

Based on the above criteria the following operational periods were evaluated to determine the membrane filtration design flux rates. The cleaning interval per period was calculated based on the potential for the TMP to exceed the 0.3 bar operating criteria. A summary of the tested flux rates is given in **Table 20**.

Table 20: Norit MBR tested flux rates

No	Description	Start	End	No. of online days	Inst. Permeate flow m^3/h	Inst. Flux (lmh)	Net Flux (lmh)	Initial TMP (bar)	End TMP (bar)	TMP loss bar/d	Cleaning interval days	Average MLSS mg/ℓ
1	30 lmh, low MLSS	Week 9	Week 11	11	0.87	30	26	0.223	0.444	0.022	17	3389
2	40 lmh, middle MLSS	Week 15	Week 15	5	1.2	40	38	0.241	0.311	0.014	21	6508
3	35 lmh, middle MLSS	Week 21	Week 22	8	1.0	35	32	0.197	0.347	0.018	17	5922
4	35 lmh, low MLSS	Week 42	Week 43	8	1.0	35	32	0.122	0.231	0.014	21	3296
5	45 lmh, middle MLSS	Week 50	Week 51	5	1.3	45	43	0.270	0.356	0.017	18	5176
6	45 lmh, rising MLSS	Week 51	Week 52	8	1.3	45	43	0.183	0.326	0.018	17	7276
7	45 lmh, stable MLSS	Week 53	Week 53	5	1.3	45	42	0.216	0.221	0.001	300	7134

The predicted average daily flux rate is 37.5 lmh and the predicted cleaning frequency with average daily flux is 7-8 weeks/cleaning.

5.3 Quantification of Treatment Efficacy

Table 21 and **Table 22** summarize the permeate water quality from the Toray and Norit MBR pilot plants. Some of these parameters are illustrated graphically in **Figures 18 - 31**. The permeate water quality results are discussed further in the following sections.

Table 21 Toray MBR permeate water quality

Parameter	Units	No. of Analysis	Average	Median	Minimum	Maximum	Std Dev.
Alkalinity	mg/l CaCO3	66	130	126	41	325	48
Conductivity	mg/l	109	65	64	44	89	9
TDS	mg/l	60	411	419	265	602	65
Turbidity	mg/l	109	0.37	0.31	0.11	2.26	0.3
BOD	mg/l	23	4.8	2.8	1.5	36	7.2
COD	mg/l	111	23	20*	20*	73	9
Coliforms	CFU/100 ml	28	60	16	0	345	90
Coliphages	PFU/100 ml	32	37	7	0	261	60
E.Coli	CFU/100 ml	30	7.1	1	0	104	19.6
TKN	mg/l	104	7	3	0.5*	38	8
Ammonia	mg/l	110	2.9	0.5	0.5*	23	4.8
Nitrite	mg/l	111	0.52	0.5	0.5*	1.29	0.1
Nitrate	mg/l	111	6.3	6.1	0.8	24	5.1
Oil & Grease	mg/l	63	1.5	1.2*	1.2*	12	1.6
SRP	mg/l	109	2.6	1.3	0.1	19	3.6
TP	mg/l	61	2.7	1.26	0.5	23	4
UV_{254}	cm^{-1}	107	0.11	0.11	0.01	0.23	0

*Detection Limit

Table 22 Norit MBR permeate water quality

Parameter	Units	No. of Analysis	Average	Median	Minimum	Maximum	Std Dev.
Alkalinity	mg/ℓ	106	141	133	10	346	55
Conductivity	mg/ℓ	174	69	69	45	131	10
TDS	mg/ℓ	108	444	432	286	736	78
Turbidity	mg/ℓ	177	0.44	0.34	0.12	3	0.3
BOD	mg/ℓ	42	4.8	2.9	1	14.1	2.8
COD	mg/ℓ	181	23	20	20*	74	8
Coliforms	CFU/100 mℓ	58	80	7	0	1203	214
Coliphages	PFU/100 mℓ	59	0.1	0	0	3	0.5
E.Coli	CFU/100 mℓ	58	0.4	0	0	10	1.7
TKN	mg/ℓ	147	6.5	3	0.84	39	7.6
Ammonia	mg/ℓ	184	3.8	0.6	0.5*	29.6	6
Nitrite	mg/ℓ	182	0.8	0.5	0.5*	4.83	0.8
Nitrate	mg/ℓ	181	3.8	2.5	0.5*	15.7	3.7
Oil & Grease	mg/ℓ	116	1.7	1.2	1.2	20	2.3
SRP	mg/ℓ	162	1.9	0.9	0.1	9.5	2.2
TP	mg/ℓ	89	3.3	1.9	0.5	21	3.8
UV_{254}	cm^{-1}	136	0.1	0.1	0.01	1.6	0.2

*Detection Limit

5.3.1 Particulate removal

Figure 18 and **Figure 19** show the influent and permeate turbidity concentrations for the Toray and Norit MBR pilot plants. The influent turbidity concentration in the Toray MBR ranged from 20 – 478 NTU with a median value of 87 NTU. The permeate turbidity concentration ranged from 0.11 – 2.26 NTU with a median value of 0.31 NTU.

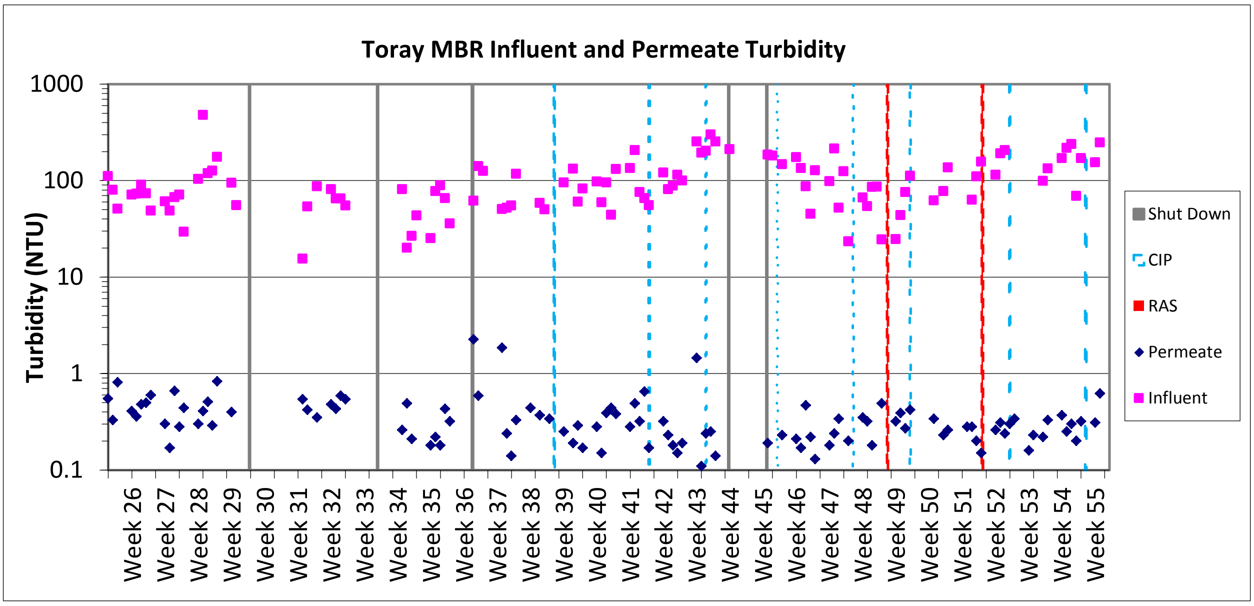

Figure 18: Toray MBR Influent and Permeate Turbidity

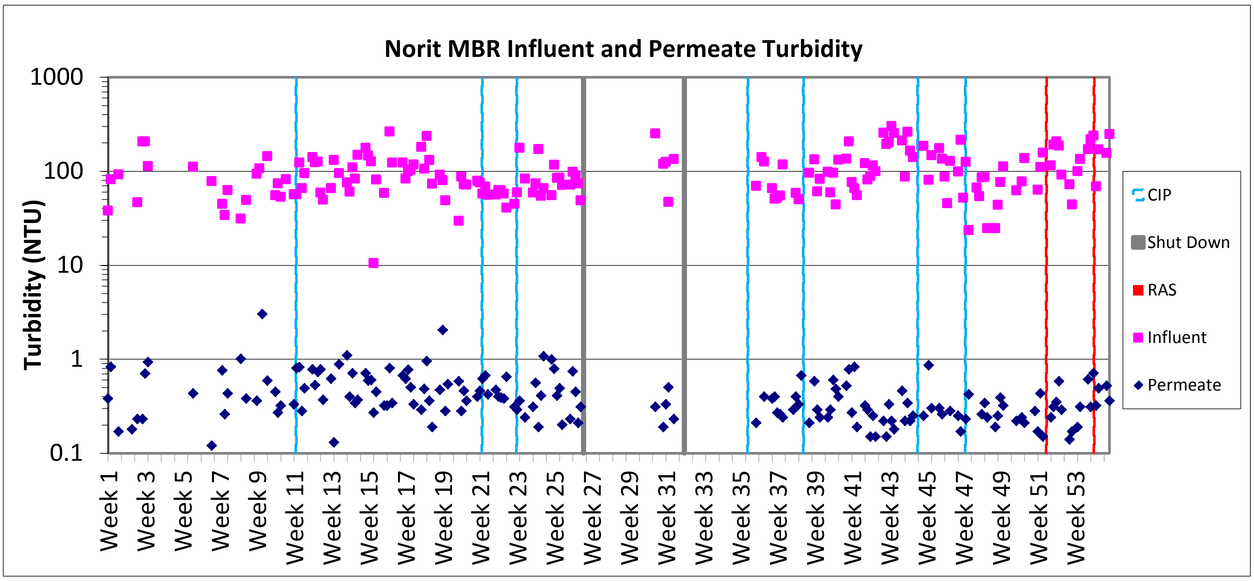

Figure 19: Norit MBR Influent and Permeate Turbidity

The Norit influent turbidity concentration ranged from 11 – 301 NTU with a median value of 86 NTU. The permeate turbidity concentration ranged from 0.12 – 3 NTU with a median value of 0.34 NTU.

The low turbidity of the permeate achieved throughout the experimental period showed that the membranes maintained their integrity. The projects permeate design specification and the manufacturers for turbidity are both <1 NTU. Both membranes performed according to specification during the study period. The percentage removal (NTU) for the Toray and Norit was 99.45% and 99.46% respectively.

5.3.2 COD removal

Figure 20 shows the influent and permeate COD concentrations for the Toray MBR pilot plant. The influent COD concentration for the Toray pilot plant ranged from 45 – 546 mg/ℓ with a median value of 261 mg/ℓ. The permeate COD concentration ranged from 20 – 73 mg/ℓ with a median value of 20 mg/ℓ.

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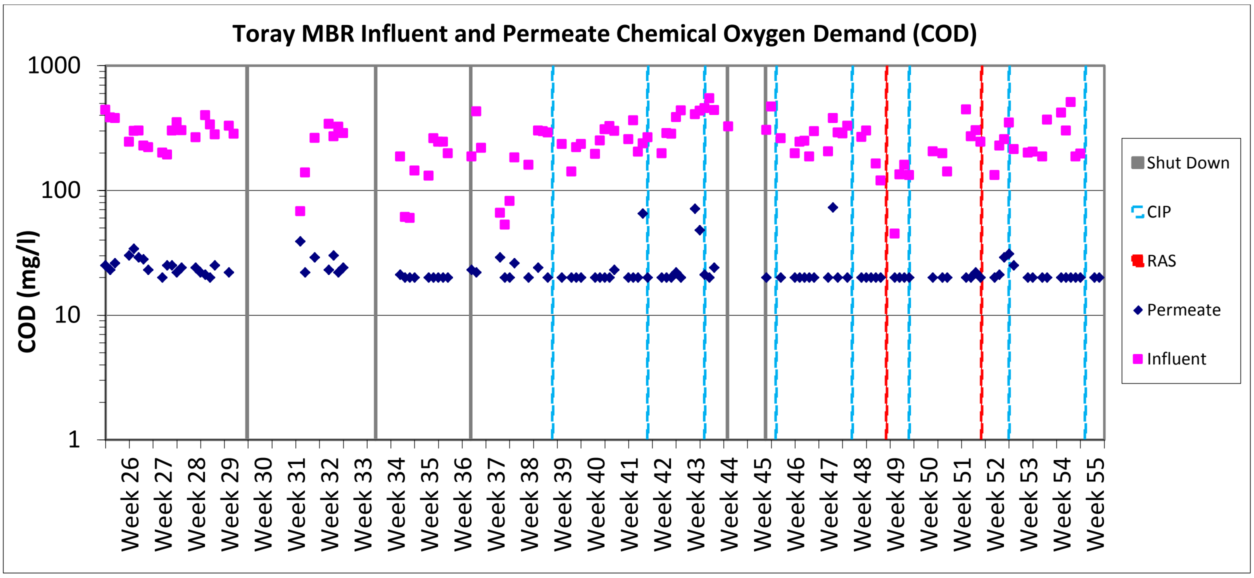

Figure 20: Toray MBR Influent and Permeate COD

Figure 21 shows the influent and permeate COD concentrations for the Norit MBR pilot plant. The influent COD concentration ranged from 45 – 874 mg/ℓ with a median value of 301 mg/ℓ. The permeate COD concentration ranged from 20 – 74 mg/ℓ with a median value of 20 mg/ℓ.

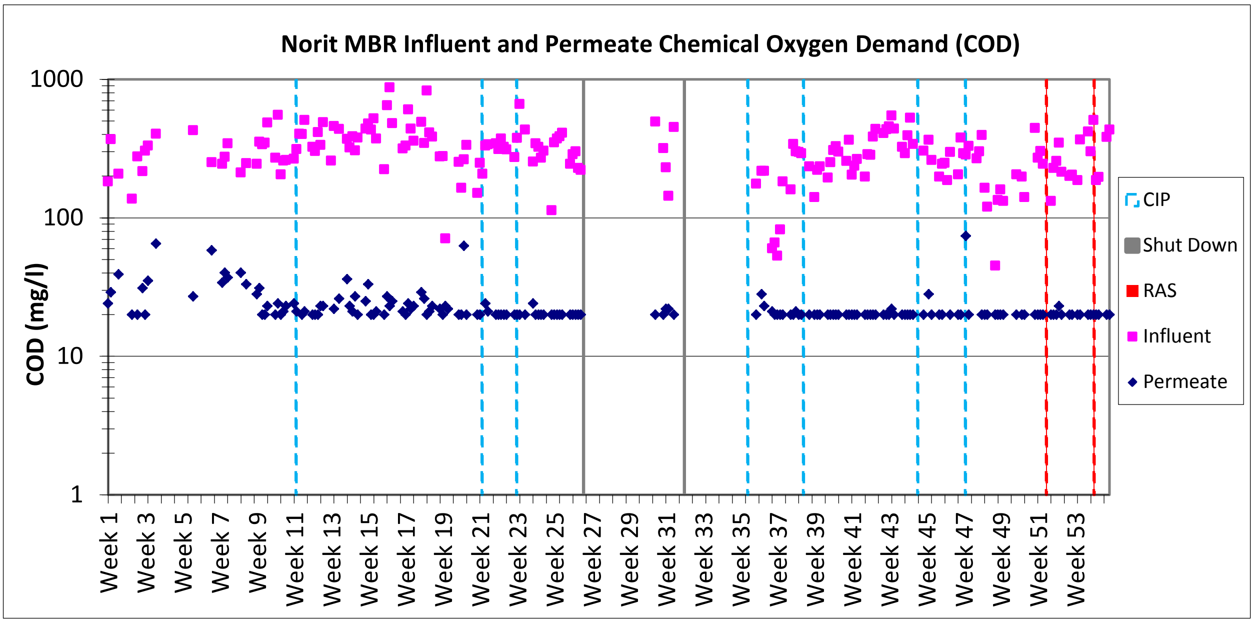

Figure 21: Norit MBR Influent and Permeate COD

The permeate COD (COD_p) results are constrained by the Umgeni Water laboratory detection limit of 20 mg/ℓ. The projects permeate design specification of a permeate COD_p = 10 mg/ℓ could not be determined because of the analytical limitations of COD measurement. Fluctuations in COD in the feed wastewater can be seen as would be expected on a full-scale plant. These fluctuations are rare in the permeate COD. The results are considered relatively good considering the disruptions to the demonstration plant biological process. The Toray specification of COD_p <50 mg/ℓ was very conservative and was comfortably achieved. Norit did not provide a specification for permeate COD as COD removal is for the most part dependent on the performance of the biological process and not the membrane.

The percentage removal (COD) for the Toray and Norit plants was 89% and 91% respectively.

5.3.3 Inorganic nitrogen removal

Figure 22 shows the influent and permeate Ammonia (NH_3) concentrations for the Toray MBR pilot plant. The pilot plant was designed to operate in nitrification and denitrification mode. The influent NH_3 concentration ranged from 5 – 30 mg/ℓ with a median value of 19 mg/ℓ. The permeate NH_3 concentration ranged from 0.5 – 23 mg/ℓ with a median value of 0.5 mg/ℓ. Complete nitrification was therefore achieved for much of the plant operating period. The projects permeate design specification of <0.5 mg/ℓ NH_3 was thus achieved when the biological process was stable.

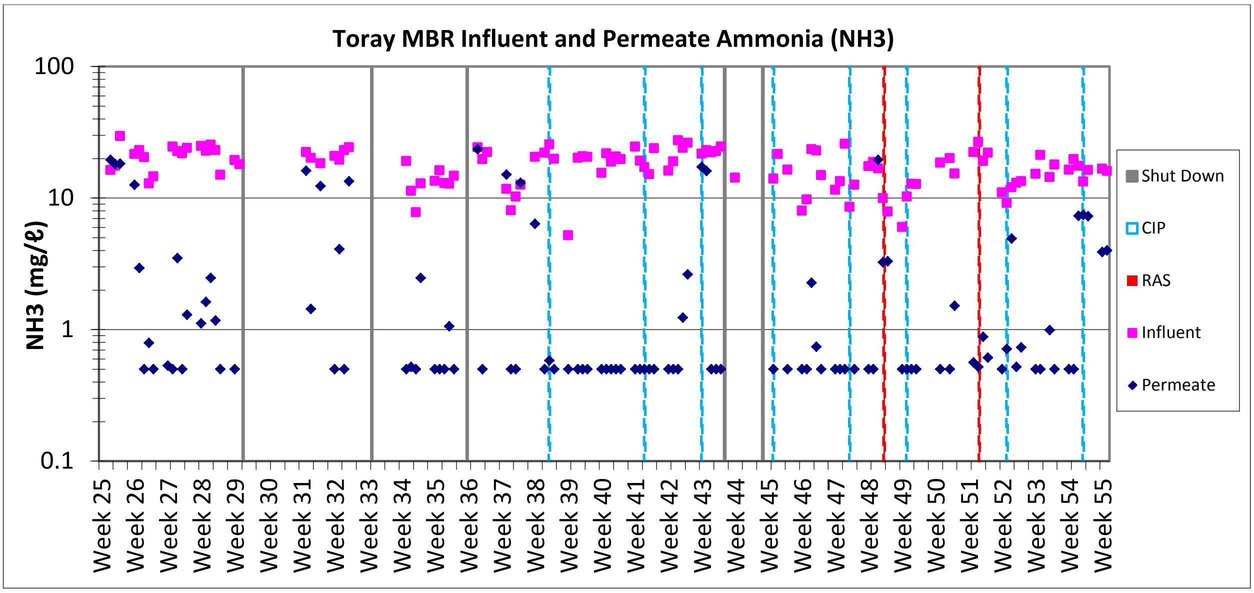

Figure 22: Toray MBR Influent and Permeate Ammonia

The permeate Nitrate (NO_3) concentration ranged from 0.8 – 24 mg/ℓ with a median value of 6.1 mg/ℓ indicating partial denitrification. The projects permeate design specification of 6 mg/ℓ NO_3 was thus not achieved. The denitrification process did not run as well as expected as is illustrated by **Figure 23**. Part of the reason for this may have been due to the over oxygenation of the anoxic zone. Because of the high air scouring rates in the Toray membrane tank, the mixed liquor becomes relatively saturated in dissolved oxygen (DO) so that the high flow RAS stream is rich in DO. As the RAS stream is returned directly to the anoxic zone, this flow may deplete the influent readily biodegradable COD (RBCOD) needed for denitrification.

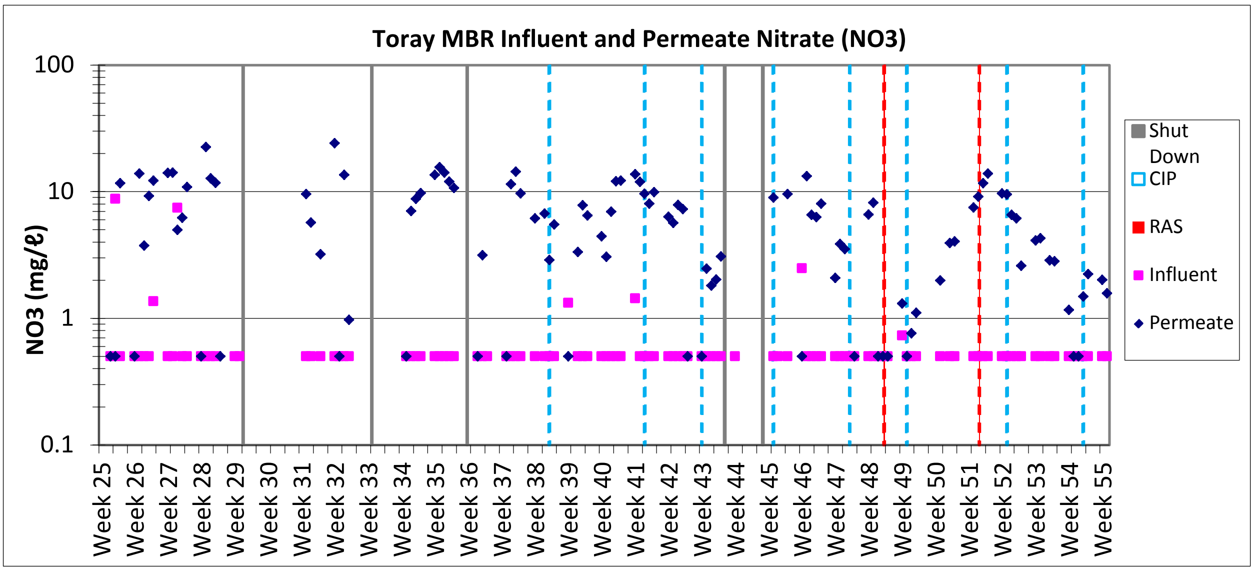

Figure 23 Toray MBR Influent and Permeate Nitrate

Figure 24 shows the influent and permeate Ammonia (NH_3) concentrations for the Norit MBR pilot plant. The influent NH_3 concentration ranged from 0.5 – 57 mg/ℓ with a median value of 22 mg/ℓ. The pilot was designed to operate in nitrification and denitrification mode. The permeate NH_3 concentration ranged from 0.5 – 30 mg/ℓ with a median value of 0.6 mg/ℓ, thus just over the target of 0.5 mg/ℓ.

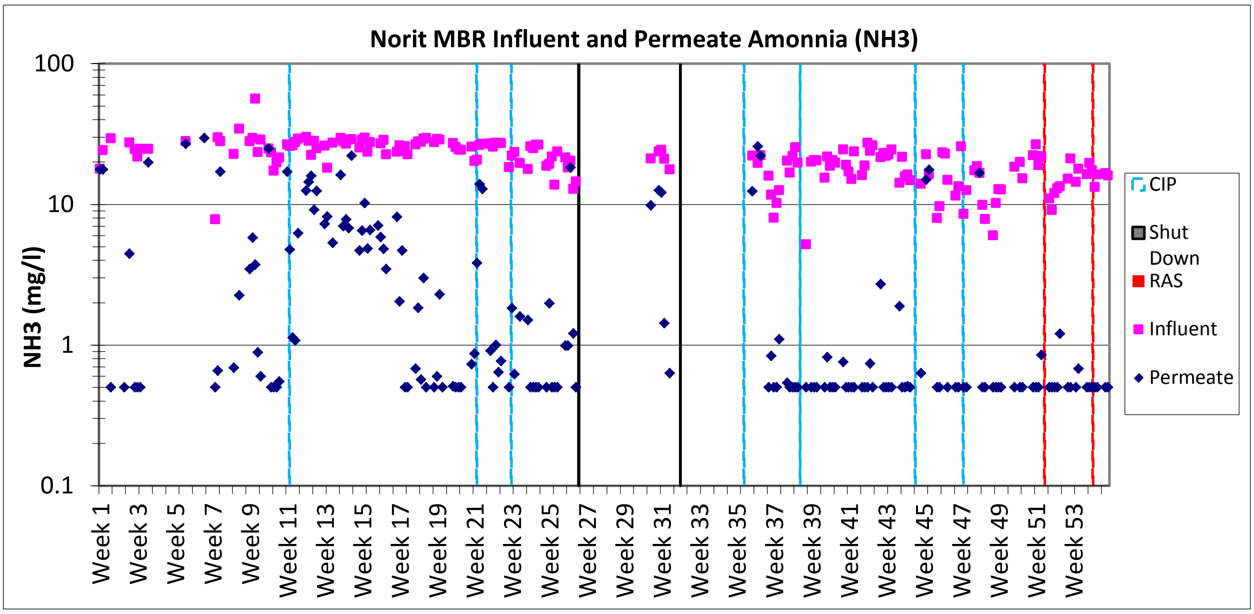

Figure 24: Norit MBR Influent and Permeate Ammonia

The permeate Nitrate (NO_3) concentration ranged from 0.5 – 15.7 mg/ℓ with a median value of 2.5 mg/ℓ. The projects permeate design specification of <6 mg/ℓ NO_3 was thus achieved. The denitrification process ran relatively well in the Norit MBR system, given the numerous operating disruptions and scale constraints. The denitrification results are illustrated in **Figure 25**.

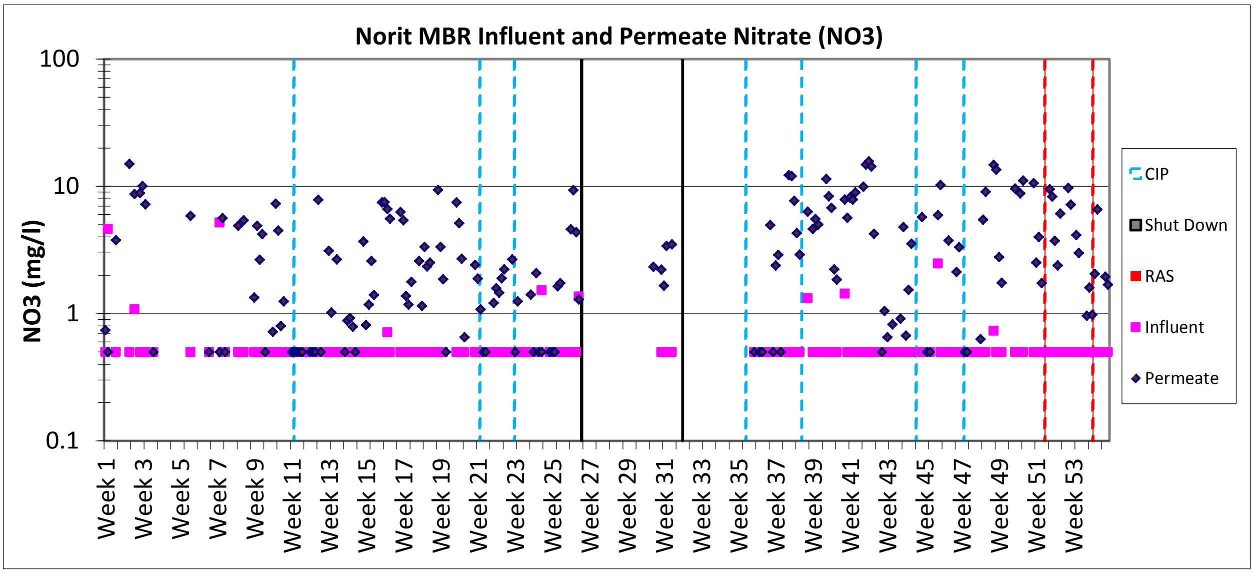

Figure 25: Norit MBR Influent and Permeate Nitrate

The projects permeate design specification was for complete nitrification (<0.5 mg/ℓ NH_3). Complete nitrification was not always achieved, especially in the first six months of the project, but an improvement in nitrification was evident during operation of the plant from Week 35 onwards. This improvement in nitrification is thought largely to be result of greater reliability in the pilot plant operation (less downtime) as well as fewer pollution incidents (biomass loss).

The nitrification process operated efficiently in the MBR systems with averages of 88% and 86% for the Toray and Norit plants respectively.

5.3.4 Toray microbial rejection

Figures 26 - 28 show the influent and permeate microbial concentrations for the Toray MBR pilot plant. The Toray MBR achieved 5-log removal of total coliforms and 6-log removal of faecal coliforms (*E.Coli*) and 3-log removal for coliphages. The median Toray MBR influent concentration for total coliforms, faecal coliforms (*E.Coli*) and coliphages was 3.1E+06 CFU/100 mℓ, 1.9E+06 CFU/100 mℓ and 2.0E+04 PFU/100 mℓ respectively. The median Toray MBR permeate concentration for total coliforms, faecal coliforms (*E.Coli*) and coliphages was 16 CFU/100 mℓ, 1 CFU/100 mℓ and 6.5 PFU/100 mℓ respectively. The projects permeate design specification for total coliforms of <10 CFU/100 mℓ was thus not achieved. Neither was the target of 0 CFU/100 mℓ faecal coliforms (*E.Coli*) and 0 PFU/100 mℓ coliphages.

It is suspected that biological growth on the Toray permeate lines could be a contributing factor to the total coliforms result being slightly higher than the target. On a full scale plant the permeate line would be chlorinated thus avoiding biological growth. Out of range (OUR) faecal coliform results cannot be explained, but may in some cases be due to sample contamination. Finally, the performance of the Toray membrane clearly indicates that it is not capable of removing all coliphages (viruses). The performance of the Toray membrane at Darvill (3-log removal) replicates the Toray membrane performance at pilot plant trials held at Point Loma (**Section 3.4.4**).

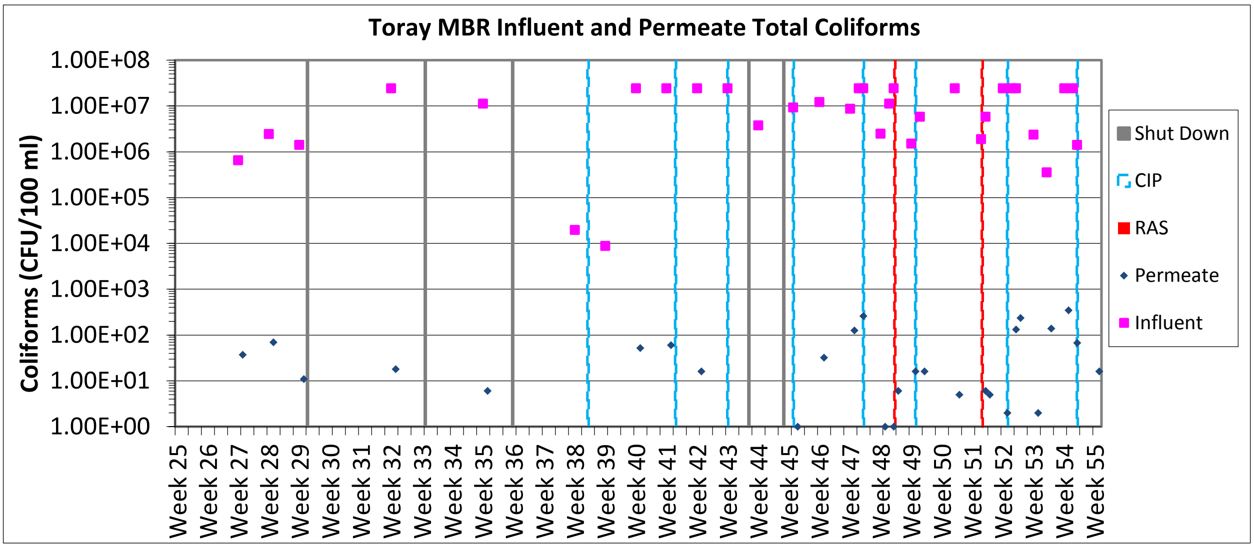

Figure 26: Toray MBR Influent and Permeate Total Coliforms

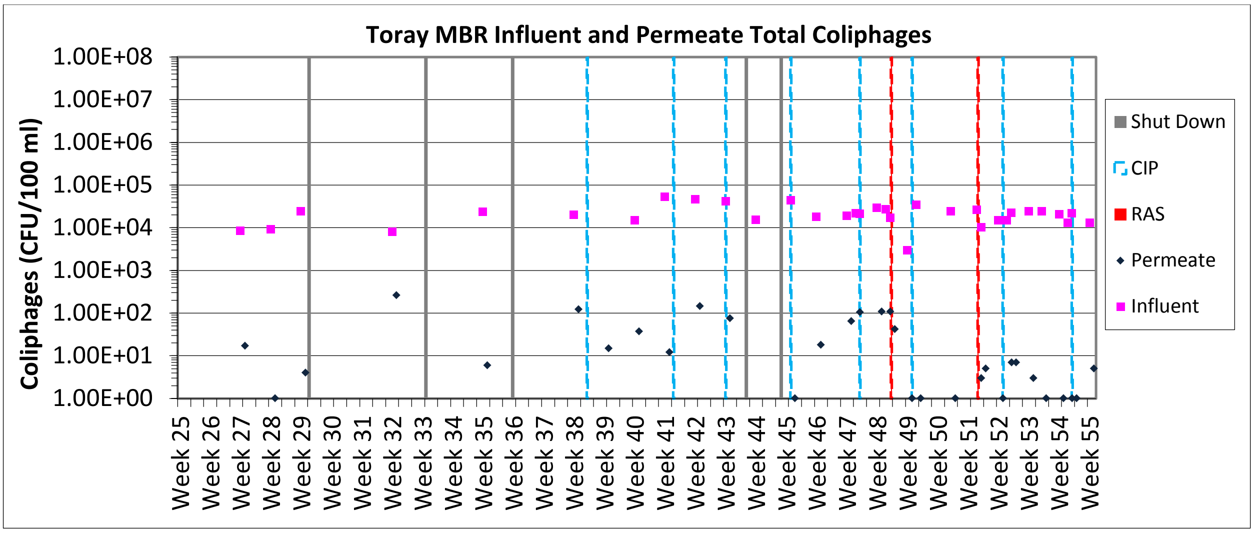

Figure 27: Toray MBR Influent and Permeate Coliphages

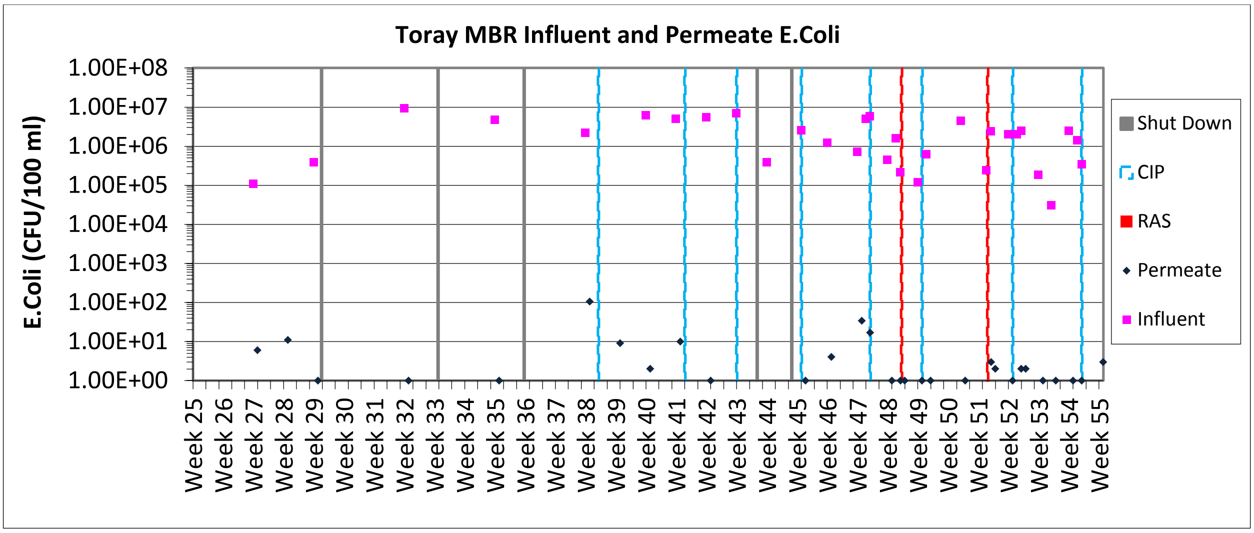

Figure 28: Toray MBR Influent and Permeate E.Coli

5.3.5 Norit microbial rejection

Figure 29 - 31 show the influent and permeate microbial concentrations for the Norit MBR pilot plant. The Norit MBR achieved greater than 6-log removal of faecal coliforms (*E.Coli*) and 5-log removal for total coliforms and coliphages. The median Norit MBR influent concentration for total coliforms, faecal coliforms (*E.Coli*) and coliphages was 2.4E+06 CFU/100 mℓ, 1.2E+06 CFU/100 mℓ and 1.2E+04 PFU/100 mℓ respectively. The median Norit MBR permeate concentration for total coliforms, faecal coliforms (*E.Coli*) and coliphages was 11 CFU/100 mℓ, 0 CFU/100 mℓ and 0 PFU/100 mℓ respectively. The projects permeate design specification for total coliforms of <10 CFU/100 ml was therefore almost achieved and the target of 0 CFU/100 mℓ faecal coliforms (*E.Coli*) and 0 PFU/100 mℓ coliphages was achieved. The faecal coliform and coliphage levels in the Norit MBR permeate were found below the detection limit for most of the samples collected during the normal operation of the plant.

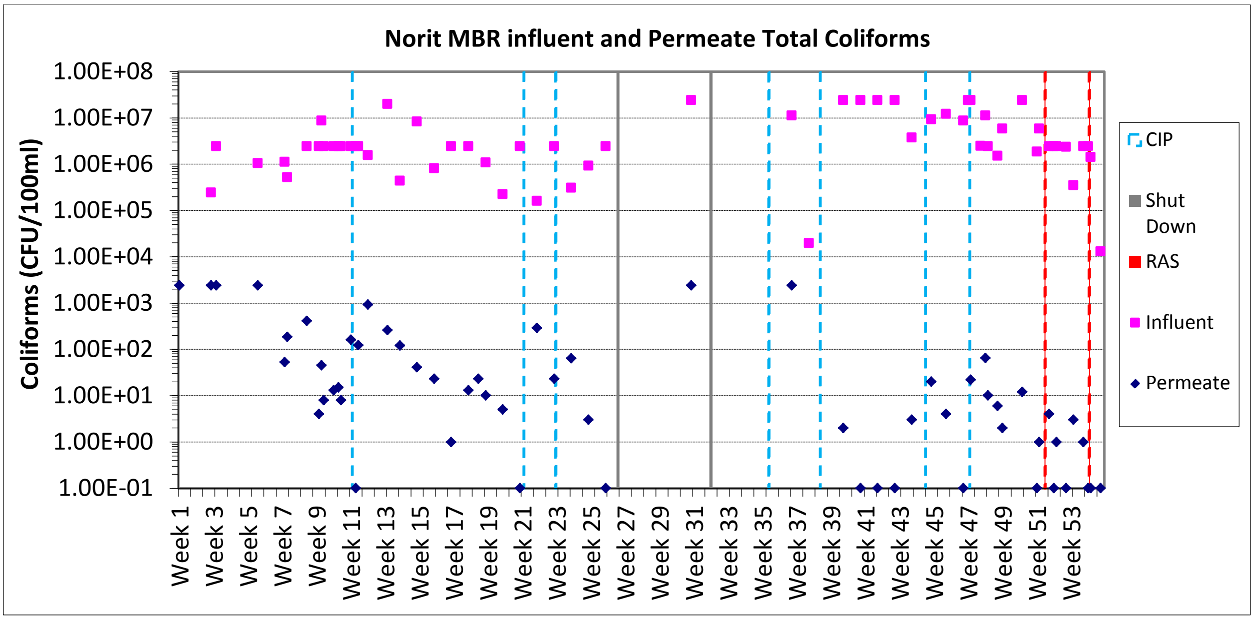

Figure 29: Norit MBR Influent and Permeate Total Coliforms

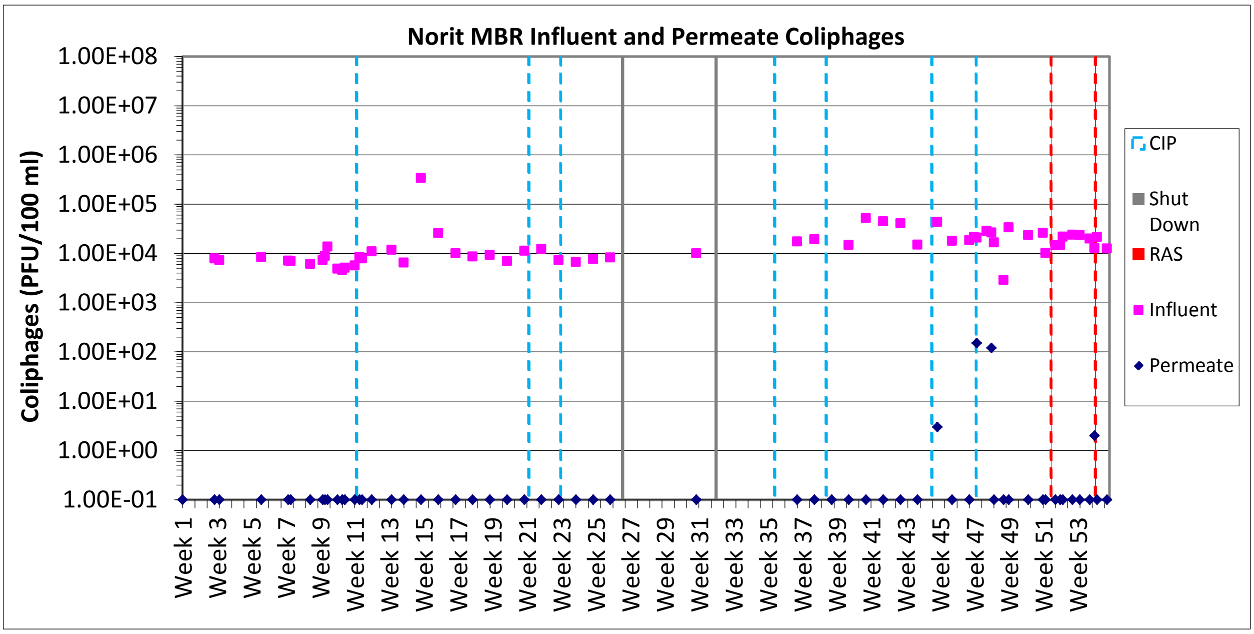

Figure 30: Norit MBR Influent and Permeate Coliphages

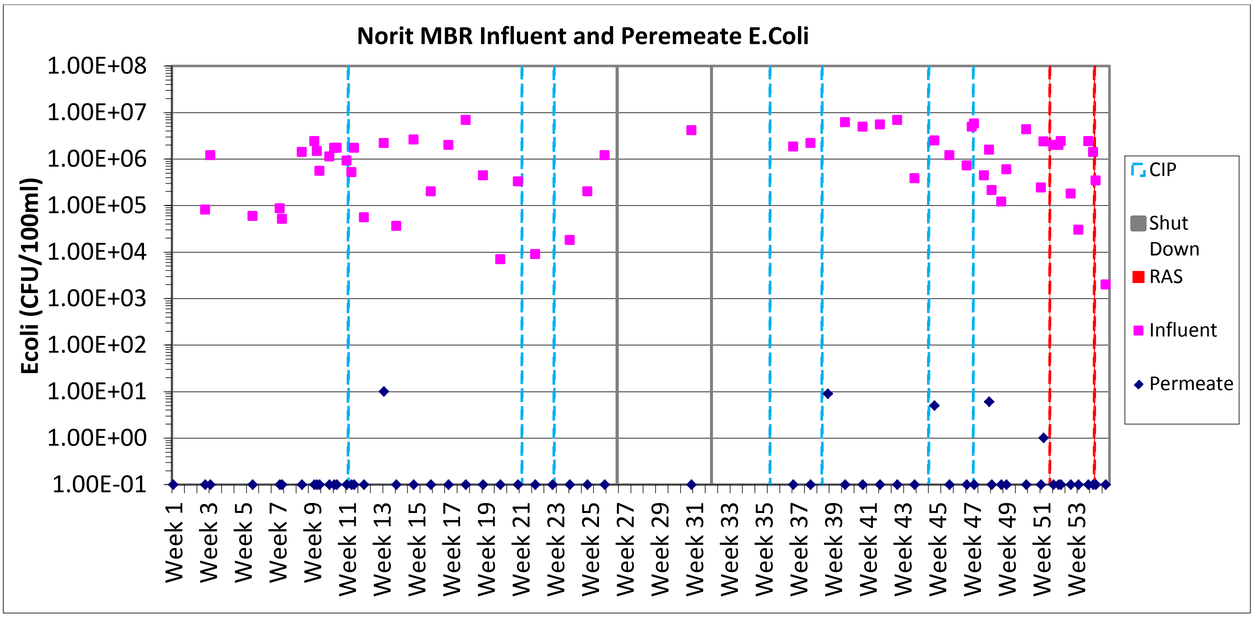

Figure 31: Norit MBR Influent and Permeate E.Coli

Both membranes achieved 5-log and 6-log removal for total coliforms and E.Coli respectively. The Norit membrane out performed the Toray membrane achieving 5-log removal for coliphages, against only 3-log removal. The beter performance is most likely due to the Norit (0.03 µm) membrane having a smaller nominal pore size than the Toray (0.08 µm) membrane. Both can be classified as Ultra-filtration membranes (0.01 -0.1 µm), but the Toray membrane is closer to a Micro-filtration membrane (0.1 -10 µm).

These results replicate those achieved during previous MBR pilot plant studies at Point Loma (**Section 3.4.4**) where Puron, Huber, Toray and Norit membranes achieved 5-log removal of total coliforms and faecal coliforms (E.Coli) and more than 3-log removal of coliphages.

The relatively high total coliform counts may possibly be ascribed to contamination on the permeate side of the membranes. As there was no disinfection (chlorination) step the product water lines are subject to biological growth over time. Similar results (contamination) was experienced in the Point Loma study (**Section 3.4.1**).

It was noticeable that where a determinant value was higher than average and above the target that other determinants also exceeded their targets. This provided confirmation of some form of breakthrough or sample contamination on that day. On accassion above average permeate values would occur during or following a CIP.

5.3.6 Performance comparison summary

The performance of the MBR systems tested as Darvill proved comparable to each other and also similar to MBR systems tested in pilot studies around the world, as detailed in **Chapter 3.**

5.3.6.1 Permeate water quality

Tests conducted at Point Loma in San Diego recorded similar permeate water quality results in some parameters to those achieved at Darvill. The municipal wastewater was of similar character to Darvill, in terms of COD, ammonia and turbidity. Some differences were evident where the concentration of influent BOD and suspended solids was double that at Darvill. At Point Loma in 2009, Toray and Norit MBR systems were used, which allowed direct performance comparison with the MBR technologies used at Darvill (**Table 23**).

Table 23: MBR permeate performance comparison

	Point Loma (2004)			**Point Loma (2009)**		**Darvill (2011)**	
Water Quality Parameter	**US Filter (Average)**	**Kubota (Average)**	**Zenon (Average)**	**Toray (Median)**	**Norit (Median)**	**Toray (Avg/Med)**	**Norit (Avg/Med)**
Turbidity (NTU)	0.04	0.08	0.06	0.06	0.04	0.37 (0.31)	0.44 (0.34)
TOC (mg/ℓ)	5.8	6.5	6.8	-	-	6.2*	-
BOD5 (mg/ℓ)	<2	<2	<2	<2	<2	4.8 (2.8)	4.8 (2.9)
COD (mg/ℓ)	20.5	18.4	17.3	-	-	23 (20)	23 (20)
NH3-N (mg/ℓ)	0.25	0.6	0.71	0.2	0.2	2.9 (0.5)	3.8 (0.6)
NO3 (mg/ℓ)	23.6	2.95	21.6	9.8	4.2	6.3 (6.1)	3.8 (2.5)
NO2 (mg/ℓ)	0.03	0.02	0.02	< 1.52	< 1.52	0.52 (0.5)	0.8 (0.5)
SRP (mg/ℓ-P)	0.41	0.15	0.66	-	-	2.6 (1.3)	1.9 (0.9)
TC (CFU/100mℓ)	386	13	807	< 10	< 20	60 (16)	322 (11)
E.Coli (CFU/100mℓ)	50	3	9	< 12	< 10	7.1 (1)	0.4 (0)
Coliphage (CFU/100mℓ)	13	10	1	< 11	< 10	37 (7)	4.7 (0)

*TOC result taken from results obtained post study, after an extended period of continued operation.

Three of the five membranes (US Filter, Kubota and Toray) can be classified as microfiltration based on the nominal pore size, while Zenon and Norit are ultrafiltration membranes. The Point Loma MBR systems were operated at permeate fluxes between 20 and 41 lmh (DeCarolis and Adham, 2007) which is comparable to the 14 - 45 lmh flux rates for the Darvill MBRs.

The turbidities achieved by the Darvill MBR systems are not as low as those recorded at Point Loma. [7]As the Toray and Norit membranes used are the same at both sites the difference may possibly be attributed to turbidity instrumentation measurement accuracy. The permeate BOD, COD and TOC are all similar. The median ammonia concentrations measured in the effluent of all systems were also low (i.e., 0.2 to 0.71 mg/ℓ-N), indicating that the systems achieved complete nitrification. The concentration of nitrate in the Kubota, Toray and Norit MBR effluent was much lower (average = 5.11 mg/ℓ-N) compared with the other systems tested (average = 20 mg/ℓ-N), because these systems contained both aerobic and anoxic zones allowing for nitrification/denitrification.

It is noticeable how the best performing membranes in terms of coliphage removal were the UF membranes from Zenon and Norit. The Norit MBR, which uses a UF membane (0.03 µm) performed exceptionally well and recorded zero median values for E.Coli and coliphages.

5.3.6.2 Membrane performance

Based on the results obtained from the pilot studies, a significant difference was observed in the operating flux of the submerged MBR systems and external MBR system. The median net flux for submerged MBR systems was measured between 17 –27 lmh whereas that for an external MBR system was measured at 37.5 - 46 lmh. The high-flux operation of the external MBR system may be attributed to better turbulence available within the external membrane module due to a relatively higher recirculation flow requirement compared to submerged MBR systems.

5.4 Statistical Analysis

5.4.1 MBR comparison

The student t-test and F-test were used to compare the performance of the two MBR systems in terms of the permeate water quality produced. The t-test compares whether the population means of two

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[7] Turbidity meters should have a resolution of 0.02 NTU or better in water with a turbidity of less than 1 NTU (US EPA, 2009). Umgeni Water laboratory detection limit for turbidity is 0.2 NTU.

independently sampled variables are the same. Similarly the F-test compares the variances of the two samples.

The results of these tests are given in **Table 24 & 25** below. Of eleven variables tested eight had means where the Null Hypotheses (H_0) could not be rejected. In other words the means are not considered statistically different. This held true for turbidity, conductivity, ammonia, TKN, SRP, COD, total coliforms and UV. The performance of the two MBRs with respect to the removal of these contaminants can therefore be considered the same.

The capability of the two membranes to reject particulate matter and micro-organisms (total coliforms) was therefore the same. For turbidity the variance was not statistically significant, but for coliform removal there was a statistically significant difference (p=0.05). In Norit the variance was higher, which potentially could indicate some form of breakthrough or contamination. This result is, however, conflicting with the results obtained for coliphage removal. The performance of the Norit membrane was superior to the Toray membrane and the means and variance were statistically different (p=0.05). One would expect that if the rejection of viruses (coliphages) in Norit was better than in Toray that the same would hold true for coliform rejection.

Table 24 Comparison of MBR permeate means – Norit and Toray (t-test) results

Variable	Null Hypothesis	Alternative	t-calculated	t-critical (α=0.05)	Fail to reject / Reject H_0
NTU	$H_o: \mu_1 = \mu_2$	$H_1: \mu_1 \neq \mu_2$	1.82	1.97	Fail to reject
EC	$H_o: \mu_1 = \mu_2$	$H_1: \mu_1 \neq \mu_2$	5×10^{-5}	1.96	Fail to reject
Ammonia	$H_o: \mu_1 = \mu_2$	$H_1: \mu_1 \neq \mu_2$	1.15	1.96	Fail to reject
Nitrate	$H_o: \mu_1 = \mu_2$	$H_1: \mu_1 \neq \mu_2$	4.46	1.97	Reject
TKN	$H_o: \mu_1 = \mu_2$	$H_1: \mu_1 \neq \mu_2$	0.38	1.97	Fail to reject
SRP	$H_o: \mu_1 = \mu_2$	$H_1: \mu_1 \neq \mu_2$	1.92	1.97	Fail to reject
TP	$H_o: \mu_1 = \mu_2$	$H_1: \mu_1 \neq \mu_2$	2.22	1.97	Reject
COD	$H_o: \mu_1 = \mu_2$	$H_1: \mu_1 \neq \mu_2$	0.64	1.97	Fail to reject
Coliforms	$H_o: \mu_1 = \mu_2$	$H_1: \mu_1 \neq \mu_2$	0.97	1.99	Fail to reject
Coliphages	$H_o: \mu_1 = \mu_2$	$H_1: \mu_1 \neq \mu_2$	3.51	2.03	Reject
UV	$H_o: \mu_1 = \mu_2$	$H_1: \mu_1 \neq \mu_2$	0.87	1.97	Fail to reject

Table 25 Comparison of MBR permeate variance – Norit and Toray (F-test) results

Variable	Null Hypothesis	Alternative	F-calculated	F-critical (α=0.05)	Fail to reject / Reject H_0
NTU	$H_{o:}\ \sigma^2_x = \sigma^2_Y$	$H_{1:}\sigma^2_x \neq \sigma^2_Y$	1.11	1.33	Fail to reject
EC	$H_{o:}\ \sigma^2_x = \sigma^2_Y$	$H_{1:}\sigma^2_x \neq \sigma^2_Y$	1.00	1.28	Fail to reject
Ammonia	$H_{o:}\ \sigma^2_x = \sigma^2_Y$	$H_{1:}\sigma^2_x \neq \sigma^2_Y$	1.35	1.33	Reject
Nitrate	$H_{o:}\ \sigma^2_x = \sigma^2_Y$	$H_{1:}\sigma^2_x \neq \sigma^2_Y$	1.94	1.31	Reject
TKN	$H_{o:}\ \sigma^2_x = \sigma^2_Y$	$H_{1:}\sigma^2_x \neq \sigma^2_Y$	1.05	1.34	Fail to reject
SRP	$H_{o:}\ \sigma^2_x = \sigma^2_Y$	$H_{1:}\sigma^2_x \neq \sigma^2_Y$	2.56	1.33	Reject
TP	$H_{o:}\ \sigma^2_x = \sigma^2_Y$	$H_{1:}\sigma^2_x \neq \sigma^2_Y$	2.44	1.5	Reject
COD	$H_{o:}\ \sigma^2_x = \sigma^2_Y$	$H_{1:}\sigma^2_x \neq \sigma^2_Y$	1.40	1.31	Reject
Coliforms	$H_{o:}\ \sigma^2_x = \sigma^2_Y$	$H_{1:}\sigma^2_x \neq \sigma^2_Y$	7.29	1.69	Reject
Coliphages	$H_{o:}\ \sigma^2_x = \sigma^2_Y$	$H_{1:}\sigma^2_x \neq \sigma^2_Y$	15971	1.65	Reject
UV	$H_{o:}\ \sigma^2_x = \sigma^2_Y$	$H_{1:}\sigma^2_x \neq \sigma^2_Y$	18	1.36	Reject

In terms of biological nutrient removal, namely ammonia, nitrate and ortho-phosphate there was a minor difference in performance. Nitrification (ammonia removal) could not be separated statistically although the variance was statistically significant, with the Norit plant showing more variability. Denitrification was statistically significant in both mean and variance with the Toray plant having a larger mean and more variability. A more stable anoxic environment in the Norit MBR and an over-aerated anoxic tank in the Toray MBR are believed to be contributing factors to this result. Similarly TP removal was better in the Norit plant, at a statistically significant level for both mean and variance. This was undoubtedly helped by the presence of an anaerobic zone in the Norit plant.

Finally the performance of both plants was comparable with respect to organics removal with no statistical difference being apparent for permeate COD and UV results. There was, however, great variability evident in the Toray plant.

Overall the performance of the two plants was comparable to a large degree. Where differences occurred they were spread fairly equally, each plant performing better on occasion. There was no conclusive evidence that one plant outperformed the other in terms of treatment capability. Of course there are other factors such as operating cost that would play a major role in any overall evaluation.

5.4.2 Darvill comparison

There are only six variables that can be compared between the MBR and Darvill WWW final effluent. Suspended solids were not compared as the MBR systems use turbidity as a measure of suspended solids removal, so direct comparison was not possible. Additionally the lower limit of SS concentration analysed for by the Umgeni Water laboratory is 4 mg/ℓ, thus rendering fair comparison impossible, as in reality the SS concentration would be much lower.

Comparison was made between the Norit MBR and Darvill as the process in the Norit pilot plant was similar to that of the Darvill plant. The results of a comparison of means (t-test) and variance (F-test) between the two plants are given in **Table 26 & 27**.

Table 26 Comparison of permeate means – Norit MBR and Darvill WWW (t-test) results

Variable	Null Hypothesis	Alternative	t-calculated	t-critical (α=0.05)	Fail to reject / Reject H_0
Conductivity	H_o: $\mu_1 = \mu_2$	H_1: $\mu_1 \neq \mu_2$	-6.9	1.96	Reject
Ammonia	H_o: $\mu_1 = \mu_2$	H_1: $\mu_1 \neq \mu_2$	-12.96	1.96	Reject
Nitrate	H_o: $\mu_1 = \mu_2$	H_1: $\mu_1 \neq \mu_2$	10.10	1.97	Reject
SRP	H_o: $\mu_1 = \mu_2$	H_1: $\mu_1 \neq \mu_2$	7.43	1.97	Reject
COD	H_o: $\mu_1 = \mu_2$	H_1: $\mu_1 \neq \mu_2$	-12.03	1.96	Reject
E.Coli	H_o: $\mu_1 = \mu_2$	H_1: $\mu_1 \neq \mu_2$	-2.93	1.96	Reject

Average Ortho-Phosphate (SRP) removal in the Darvill WWW (0.52 mg/ℓ) is significantly different (p =0.05) from the Norit MBR (1.85 mg/ℓ). Phosphate removal in the Darvill plant is however enhanced through the addition of a coagulant.

Average COD removal in the Norit MBR (23 mg/ℓ) was statistically different from the Darvill WWW (47 mg/ℓ). While both concentrations comply with the General Authorisation discharge standard of 75 mg/ℓ the potential reduction in COD entering the river downstream of Darvill, which could be achieved with an MBR retrofit would be significant.

Nitrification (average NH_3 removal) was better in the Norit plant (3.76 mg/ℓ) than in the Darvill WWW (13.43 mg/ℓ) and the difference was statistically significant (p = 0.05). The extended SRT (> 50 days) of the MBRs is conducive to the growth of nitrifying bacteria thus enhancing nitrification. The Darvill WWW has at times had a SRT of 12 days and nitrifying bacteria are slow growing and normally require an SRT > 15 days to be effective. This may have negatively impacted upon nitrification at Darvill.

Denitrification (average NO_3 removal) in the Norit MBR was 3.83 mg/ℓ and Darvill 1.01 mg/ℓ, which was statistically significantly different (p=0.05). This would suggest the Darvill WWW is operating optimally, which we know from other determinants it is not. The Darvill nitrification process (the conversion of NH_3 into NO_3) is not working that efficiently with 70% of ammonia effluent concentrations exceeding the standard of 6 mg/ℓ. It may be the case that nitrification is not occurring throughout the aerobic basin and thus denitrification is being effected.

The average E.Coli value in the Norit permeate (0.4 CFU/100 ml) was statistically significantly different (p =0.05) from the Darvill WWW (11009 CFU/100 ml), illustrating the effectiveness of membrane processes on microbiological contaminant removal.

In terms of the comparison of variance between the variables considered all were statistically significantly different (**Table 27**). The Darvill WWW showed greater variability for all variables except for SRP removal. It would appear that the Norit pilot plant despite its many operational problems maintained a more consistent process than the Darvill WWW and could be said to have a more reliable process. This hypothesis is explored in more detail in the following section by performing a reliability analysis using the coefficient of reliability (COR) methodology developed by Niku et al. (1979).

Table 27 Comparison of permeate variance – Norit MBR and Darvill WWW (F-test) results

Variable	Null Hypothesis	Alternative	F-calculated	F-critical (α=0.05)	Fail to reject / Reject H_0
Conductivity	$H_{0:}\ \sigma^2_x = \sigma^2_Y$	$H_{1:}\sigma^2_x \neq \sigma^2_Y$	1.38	1.26	Reject
Ammonia	$H_{0:}\ \sigma^2_x = \sigma^2_Y$	$H_{0:}\ \sigma^2_x = \sigma^2_Y$	2.21	1.26	Reject
Nitrate	$H_{0:}\ \sigma^2_x = \sigma^2_Y$	$H_{0:}\ \sigma^2_x = \sigma^2_Y$	9.95	1.25	Reject
SRP	$H_{0:}\ \sigma^2_x = \sigma^2_Y$	$H_{0:}\ \sigma^2_x = \sigma^2_Y$	14.22	1.26	Reject
COD	$H_{0:}\ \sigma^2_x = \sigma^2_Y$	$H_{0:}\ \sigma^2_x = \sigma^2_Y$	15.92	1.23	Reject
E.Coli	$H_{0:}\ \sigma^2_x = \sigma^2_Y$	$H_{0:}\ \sigma^2_x = \sigma^2_Y$	8.8×10^7	1.66	Reject

The statistical analyses performed above indicate that there are statistical significant differences in the water quality produced by the MBRs in comparison to the Darvill WWW for the same period of operation. The variance or variability of the process was also statistical significant with the Darvill WWW showing more variability. These results are confirmed when analysing the median effluent / permeate water quality results as presented in **Table 28**.

Table 28 Comparison of effluent water quality

Parameter	Units	Darvill Final Effluent	Toray MBR Permeate	Norit MBR Permeate
		Median		
Conductivity	mS/m	77	64	69
SS	mg/l	17	<4	<4
COD	mg/l	41	<20	<20
E.Coli	CFU/100 ml	140	1	0
Ammonia	mg/l	13	0.5	0.5
Nitrite	mg/l	0.5	0.5	0.5
Nitrate	mg/l	0.5	6.1	0.5
O&G	mg/l	1.2	1.2	1.2
SRP	mg/l	0.3	1.3	0.1

5.5 Process Reliability Assessment

An analysis of the process reliability is undertaken in the following section using the Coefficient of Reliability (COR) method (Refer to reliability calculations in **Annexure D**). An explanation of the COR methodology is given in **Chapter 4**. The process reliability of the Norit and Toray MBRs and the Darvill WWW are compared against pre-defined performance targets. A list of determinants was chosen (**Table 29**) and the performance of the three processes compared in terms of the effectiveness and reliability of each process in removing these determinants (percentage compliance with a set standard).

The performance targets were different for the MBR Pilot Plants and the Darvill WWW as the Darvill WWW is an existing plant for which the required effluent standards have previously been defined, whereas the MBR permeate quality was chosen at the outset of this project. The Darvill WWW effluent discharge standard is as defined by a General Authorisation issued by the Department of Water Affairs & Sanitation. The MBR permeate water quality targets are based on a literature review of performance targets set on previous studies of similar nature. This had the added advantage of allowing comparison with other studies to a certain degree. Only seven determinants were common to both and therefore could be used for comparison purposes.

The application of the COR methodology affords the water treatment plant operator the opportunity to make process decisions based on the anticipated performance of individual processes. Where these individual processes are failing to meet certain standards or operational guidelines more demanding thresholds can be targeted. The gap between the target and the standard depends on the actual variation of the concentration (quantified by the coefficient of variation) and by the confidence threshold selected for processing the coefficient of variation (Djeddou et al., 2013).

Table 29 MBR target and Darvill effluent discharge standards

Parameter	**Units**	**MBR Target**	**Darvill Permit**
BOD_5	mg/ℓ	2	10
COD	mg/ℓ	20	75
Conductivity	mS/m	75	
TSS	mg/ℓ	<1	25
Turbidity (NTU)	mg/ℓ	<1	
Oil &Grease	mg/ℓ	<1.2	
Ammonia (NH_3-N)	mg/ℓ	0.5	6
Nitrate (NO_3) as N	mg/ℓ	<6	15
Nitrite (NO_2) as N	mg/ℓ	<2	
TKN	mg/ℓ	<10	
Orthophosphate (SRP)	mg/ℓ	1	1
Total Coliforms (CFU/100ml)	CFU/100ml	<10	
E.Coli (CFU/100ml)	CFU/100ml	0	500
Coliphage (PFU/100ml)	PFU/100ml	0	

For the COR method to be applied it is necessary for the data to have a log-normal distribution **(**Niku et al., 1979). The data must therefore be analysed to determine if it is log-normally distributed. This was done using the Kolmogorov-Smirnov (KS) test as described in Daniel (1990). The KS test is a non-parametric test that compares the sample distribution (empirical distribution) with a reference distribution, in this case the cumulative distribution function (CDF) of the log-normal distribution. The KS test quantifies a distance between the two distributions and calculates under the null hypotheses that the sample distribution is the same or different to the reference distribution (log-normal). If the data did not match the log-normal distribution then the empirical distribution was applied to determine the reliability of the process.

The results of the KS test are shown in **Table 30, 31 & 32** below. Of the fifteen variables considered seven, six and four were found to be log-normally distributed in the Toray, Norit and Darvill data. Two variables were found to be normally distributed in the Toray data and the remainder of the data had an empirical distribution. This was unfortunate as this limited the number of variables that the methodology (COR) could be applied to and was not expected. Previous studies (Niku et al., 1979; Oliveria and Sperling, 2008 and

Djeddou, et al., 2013) had shown a good-fit to the log-normal distribution for the majority of wastewater variables.

It is generally accepted practice for the data to be representative of the population for the sample size should be greater than 30 and that there be 20 or more unique values in the sample. Some variables do not meet these criteria and therefore were not analysed. The effectiveness of the individual processes in removing these variables is, however, evident in earlier analyses of permeate water quality (Refer to **Chapter 5**), where for example the Norit MBR was extremely effective at removing Coliphages (only 3 unique values).

Table 30 Results of distribution analysis (Toray permeate)

Process Unit	**Variable**	**Unit**	**Sample Size**	**Unique Values**	**Distribution**
Toray	Turbidity	NTU	107	49	Log-Normal
	Conductivity	mS/m	107	93	Log-Normal
	Total Dissolved Solids	mg/ℓ	60	51	Log-Normal
	Total Phosphorous	mg/ℓ	61	44	Log-Normal
	Ortho Phosphate (SRP)	mg/ℓ	107	58	Log-Normal
	Total Kjeldahl Nitrogen	mg/ℓ	102	38	Empirical
	Biochemical Oxygen Demand (BOD)	mg/ℓ	23	22	-
	Chemical Oxygen Demand (COD)	mg/ℓ	109	20	Empirical
	Ammonia-N	mg/ℓ-N	110	45	Empirical
	Nitrate-N	mg/ℓ-N	109	86	Normal
	Nitrite-N	mg/ℓ-N	109	9	-
	Total Coliforms	CFU/100 mℓ	38	25	Log-Normal
	Faecal Coliforms	CFU/100 mℓ	30	12	-
	Total Coliphages	PFU/100 mℓ	32	20	Log-Normal
	UV_{254}	(abs/cm)	101	65	Normal

Table 31 Results of distribution analysis (Norit permeate)

Process Unit	Variable	Unit	Sample Size	Unique Values	Distribution
Norit	Turbidity	NTU	176	71	Log-Normal
	Conductivity	mS/m	174	140	Log-Normal
	Total Dissolved Solids	mg/ℓ	108	87	Log-Normal
	Total Phosphorous	mg/ℓl	89	71	Log-Normal
	Ortho Phosphate (SRP)	mg/ℓ	162	100	Log-Normal
	Total Kjeldahl Nitrogen	mg/ℓ	149	73	Empirical
	Biochemical Oxygen Demand (BOD)	mg/ℓ	42	35	Log-Normal
	Chemical Oxygen Demand (COD)	mg/ℓ	184	22	Empirical
	Ammonia-N	mg/ℓ-N	186	89	Empirical
	Nitrate-N	mg/ℓ-N	184	137	Empirical
	Nitrite-N	mg/ℓ-N	182	31	Empirical
	Total Coliforms	CFU/100 mℓ	52	29	Log-Normal
	Faecal Coliforms	CFU/100 mℓ	58	5	-
	Total Coliphages	PFU/100 mℓ	57	3	-
	UV_{254}	(abs/cm)	138	73	Empirical

Table 32 Results of distribution analysis (Darvill final effluent)

Process Unit	Variable	Unit	Sample Size	Unique Values	Distribution
Darvill	Total Suspended Solids	mg/ℓ	240	66	Log-Normal
	Conductivity	mS/m	240	186	Log-Normal
	Ortho Phosphate (SRP)	mg/ℓ	240	77	Empirical
	Chemical Oxygen Demand (COD)	mg/ℓ	240	72	Log-Normal
	Ammonia-N	mg/ℓ-N	239	217	Empirical
	Nitrate-N	mg/ℓ-N	238	60	Empirical
	Faecal Coliforms	CFU/100 mℓ	240	105	Log-Normal

Based on the findings of the distribution analyses the COR test was conducted for those variables with log-normally distributed data only. The results are presented in terms of the expected percentage of compliance (**Table 33**) and the design mean (**Tables 34, 35 & 36**). The required percentage of compliance was 95% ($\alpha_s = 0.05$). The calculated design mean would either be required to be lowered to meet the performance requirement or it could be raised (relaxed) if the process was functioning as desired. For variables not log-normally distributed the expected percentage compliance was obtained from the empirical distribution of the data. The design mean for empirically distributed data is merely indicated by a greater than (>) or less than (<) arrow to indicate the necessity or otherwise of lowering or raising the design mean. The magnitude of the change is, however not specified.

Table 33 Expected percentage compliance results

				Percentage Compliance (%)		
Variable	**Unit**	**MBR Target**	**General Standard**	**Toray**	**Norit**	**Darvill**
Turbidity	NTU	<1		96	95	-
Suspended Solids		<1	25	-	-	65
Conductivity	mS/m		Max 250	99	99	96
Total Phosphorous	mg/ℓ	-	-	47	38	-
Ortho Phosphate (SRP)	mg/ℓ	-	1	46	53	88
TKN	mg/ℓ	<10		83	83	-
Biochemical Oxygen Demand (BOD)	mg/ℓ	2		-	93	
Chemical Oxygen Demand (COD)	mg/ℓ	20	75	69	40	85
Ammonia-N	mg/ℓ-N	0.5	6	57	6	30
Nitrate-N	mg/ℓ-N	6	15	62	76	100
Total Coliforms	CFU/100mℓ	<10		87	76	-
Faecal Coliforms	CFU/100mℓ	0	500	-	-	70
Total Coliphages	PFU/100mℓ	0		25	-	-

Table 34 Design mean results for 95% compliance (Darvill)

Process Unit	Variable	Unit	Actual Mean	Standard	Design Mean
Darvill	Total Suspended Solids	mg/ℓ	25	25	8
	Conductivity	mS/m	76	100	92
	Ortho Phosphate (SRP)	mg/ℓ	0.5	1	>
	Chemical Oxygen Demand (COD)	mg/ℓ	47	75	22
	Ammonia-N	mg/l-N	13	6	<
	Nitrate-N	mg/l-N	1	15	>
	Faecal Coliforms	CFU/100 ml	11009	500	130

Table 35 Design mean results for 95% compliance (Toray)

Process Unit	Variable	Unit	Actual Mean	Target	Design Mean
Toray	Turbidity	NTU	0.37	<1	0.40
	Conductivity	mS/m	65	75	80
	Total Dissolved Solids	mg/l	411	500	380
	Total Phosphorous	mg/l	2.7	1	0.34
	Ortho Phosphate (SRP)	mg/l	2.6	1	0.31
	Total Kjeldahl Nitrogen	mg/l	7	10	<
	Biochemical Oxygen Demand (BOD)	mg/l	4.8	2	_
	Chemical Oxygen Demand (COD)	mg/l	23	20	<
	Ammonia-N	mg/l-N	2.9	0.5	<
	Nitrate-N	mg/l-N	6.3	<6	_
	Nitrite-N	mg/l-N	0.5	<2	>
	Total Coliforms	CFU/100 ml	60	<10	3.0
	Faecal Coliforms	CFU/100 ml	7.1	0	_
	Total Coliphages	PFU/100 ml	37	0	_

Table 36 Design mean results for 95% compliance (Norit)

Process Unit	Variable	Unit	Actual Mean	Target	Design Mean
Norit	Turbidity	NTU	0.44	<1	0.42
	Conductivity	mS/m	69	100	80
	Total Dissolved Solids	mg/l	444	500	385
	Total Phosphorous	mg/l	3.3	1	0.33
	Ortho Phosphate (SRP)	mg/l	1.9	1	0.33
	Total Kjeldahl Nitrogen	mg/l	6.5	10	<
	Biochemical Oxygen Demand (BOD)	mg/l	4.8	2	0.96
	Chemical Oxygen Demand (COD)	mg/l	23	20	<
	Ammonia-N	mg/l-N	3.8	0.5	<
	Nitrate-N	mg/l-N	3.8	<6	<
	Nitrite-N	mg/l-N	0.8	<2	>
	Total Coliforms	CFU/100 ml	322	<10	2.7
	Faecal Coliforms	CFU/100 ml	0.4	0	_
	Total Coliphages	PFU/100 ml	4.7	0	_

5.5.1 Interpretation of results

As an example of how to interpret the results the Toray permeate turbidity (log-normal distribution) and the Norit permeate TKN (empirical distribution) is given below.

The target mean permeate turbidity for the Toray MBR plant is < 1 NTU. The operational (actual) mean achieved for the period of measurement is 0.37 NTU. This expected percentage compliance was 96% thus above the targeted percentage of 95% compliance. The process is operating as required and complying with the water quality specification. The process can therefore remain the same and has some inherent flexibility as the design mean can be relaxed slightly to 0.40 and still remain compliant.

For the empirically distributed TKN in the Norit permeate the target mean is 10 mg/ℓ. The operational (actual) mean achieved is 6.5 mg/ℓ. Although the mean is within the target range the process can only achieve this 83% of the time and therefore is not compliant at the 95% level. The design mean therefore needs to be lowered ("<") and the process operated more stringently to achieve compliance.

A brief discussion of the remaining results follows with the focus on notable differences in performance.

5.5.1.1 Membrane bioreactors (Toray and Norit)

Turbidity

Both MBRs achieved 95% compliance for the removal of turbidity. This was expected given the physical barrier provided by the membrane, and which is essentially the major advantage of membrane based water treatment.

Biochemical Oxygen Demand (BOD)

There was insufficient data to analyse the Toray BOD results. The Norit effluent BOD was compliant 93% of the time. The design mean would have to be lowered to 0.96 mg/ℓ to achieve 95% compliance at the 2 mg/ℓ target level.

Soluble Reactive Phosphate (SRP)

The Norit and Toray MBRs achieved 61% and 48% compliance respectively for SRP removal to the discharge standard of 1 mg/ℓ. This is expected given that the Norit MBR pilot plant included an anaerobic zone for enhanced phosphorous removal. The addition of a coagulant (aluminium sulphate) to precipitate phosphate may be required to achieve compliance. For a period an inorganic coagulant was dosed in the pilot plants feed water and this improved phosphate removal significantly.

Total Phosphorous

The Norit and Toray MBRs achieved 80 and 65% compliance respectively for TP removal to the discharge standard of 1 mg/ℓ.

Total Kjeldahl Nitrogen

The Norit and Toray MBRs both achieved 83% compliance for TKN for the discharge standard of 10mg/ℓ. The design mean will have to be reduced ("<") in order to achieve 95% compliance.

Chemical Oxygen Demand (COD)

The Toray and Norit MBRs achieved 40% and 69% compliance respectively for COD removal to the discharge standard of 20 mg/ℓ. These results must be viewed in light of the fact that the detection limit of 20 mg/ℓ may have influenced the results. Significant proportions (40%) of the results were recorded at the detection limit of 20 mg/ℓ. A number of outliers may have also skewed the data. To add further perspective the means for the Toray and Norit plants are 25 and 22 mg/ℓ respectively.

Ammonia

Percentage compliance for Toray and Norit was 62% and 6% respectively indicating significant problems with the reliability of process in the Norit plant. It must be noted that removal efficiency for the Toray and Norit plants was 88% and 87% respectively. The problems appear thus to be related directly to disruptions in the process (breakdowns) rather than the biological processes, which is supported by the operational history of the two plants, the Norit plant having the greater frequency of disruptions.

Nitrate

Percentage compliance for Toray and Norit was 62% and 76% respectively indicating denitrification was operating relatively effectively, but with room for improvement.

Total Coliforms

The Norit and Toray MBRs achieved 76% and 87% compliance respectively for TC removal to the discharge standard of 10 CFU/100 mℓ.

Coliphages

The Toray MBR achieved 25% compliance for Coliphages removal to the discharge standard of 0 CFU/100 mℓ. The Norit MBR could not be analysed for compliance as there were insufficient unique data points, the majority being 0 CFU/100 mℓ. It can thus be inferred that the Norit MBR was effective at coliphage removal.

5.5.1.2 Darvill

Suspended Solids

Suspended Solids (SS) and not turbidity is measured at the outfall from the Darvill WWW. Darvill WWW achieved 65% compliance at a discharge standard of 25 mg/ℓ. It is immediately evident that at a much more lenient threshold compared to the MBR target the conventional process had difficultly complying with the standard.

Conductivity

The Darvill WWW achieved 96% compliance for conductivity.

Soluble Reactive Phosphate (SRP)

The Darvill WWW achieved 88% compliance for SRP to the same effluent standard of 1 mg/ℓ applied to the MBR pilot plants. This showed the Darvill plant had a far more effective ortho-phosphate removal process possible due to scale of the systems. The Darvill WWW has large and well operated anaerobic and anoxic basins. The Toray plant had no anaerobic basin and therefore is was not a surprise to see that it was the lowest performer of the three processes.

Chemical Oxygen Demand (COD)

The Darvill WWW achieved 85% compliance for COD removal which at face value appears relatively effective; however, this was against an effluent discharge standard of 75 mg/ℓ. With respect to COD removal the MBR pilot plants outperformed the Darvill WWW.

Ammonia

The Darvill WWW achieved 30% compliance for NH_3 removal which represents poor performance.

Nitrate

The Darvill WWW achieved 100% compliance for NO_3 removal against a discharge standard of 15 mg/ℓ. This result has to be viewed circumspectly in light of the nitrification performance. Without nitrification ammonia is not converted into nitrate and therefore denitrification does not take place. Low nitrate values in the Darvill final effluent therefore do not represent an effective denitrification process but a poor nitrification process.

Faecal Coliforms (E.Coli)

The Darvill WWW achieved 70% compliance for E.Coli removal against a standard of 500 CFU/100 mℓ.

In order to comply with the standards 95% of the time, five of the seven determinants analysed above would require tougher (more stringent) design standards. Only SRP and conductivity currently meet the required standard.

Discussion: Compliance

Of the nine variables analysed (**Table 30**) for the Toray MBR five of these were log-normally distributed and could be analysed for compliance using the COR methodology. Of these, only three met the threshold of 95% compliance, namely, Turbidity, Conductivity and Coliphages. Ortho-phosphate (SRP) and total coliforms were not compliant and thus the design mean would have to be tightened and process and operational adjustments made accordingly. The remaining four variables were analysed using the empirical distribution and none were compliant at the 95% target. Therefore changes would have to be made to the current process in order to achieve the target.

Nine variables were also analysed (**Table 31**) for the Norit MBR, five of which are log-normally distributed. Of these, Turbidity, Conductivity and BOD achieved 95% compliance. SRP and total coliforms were not complaint and the design means would have to be reduced. The remaining four variables were analysed using the empirical distribution and none were compliant at the 95% target

Seven variables were analysed from the Darvill WWW final effluent data and four of which had log-normal distribution and were analysed using the COR methodology. Only conductivity achieved compliance at 95%. Suspended solids, COD and Faecal coliforms were not compliant and a lower design mean would thus be required. Of the remaining three variables which were analysed using the empirical distribution, none were compliant at the 95% target.

The comparative performance of the two MBR systems and the Darvill WWW can be seen in **Table 33**. The major advantage of MBR over other sewage treatment systems is the inclusion of the membrane phase separation component. Both the Toray and Norit were equally efficient at removing suspended solids to below 1 NTU. Both membranes were also very effective at removing micro-organisms and pathogens. The performance could not be interpreted using the methodologies above due to insufficient unique values, many being zero. As was illustrated in **Chapter 5**, however, log-removal values of 3 and above were obtained for both systems.

Notable difference in performance between the Norit and Toray MBRs occurred in SRP, COD, and NH_3 removal. Norit performed better in terms of SRP removal as was expected because of to the presence of an anaerobic tank and operation of the UCT process. In terms of COD removal the Norit plant provided inconsistent performance in comparison to the Toray plant with a compliance of 40% against 69% from Toray. Nitrification compliance in the Norit MBR was very poor in comparison to Toray at 6% and 57% respectively. This is a large disparity given the respective means are 3.76 (Norit) and 2.98 mg/ℓ (Toray). Although nitrification compliance in both MBR systems did not meet the target, some perspective can be obtained if the performance was measured against the General Standard of < 6 mg/ℓ as applied to the Darvill WWW. In this case the Norit and Toray MBRs would have achieved 63% and 85% respectively. In comparison Darvill achieved only 30% compliance. Relative to the performance of MBRs in other pilot studies and full-scale plants which achieved much higher (92-99%) nitrification levels (Yoon et al., 2004, Fleischer et al., 2005 and DeCarolis et al., 2009); the performance was not as good. In comparing the performance of MBR and CASP in full scale plants Yoon et al. (2004) reported enhanced nitrification was evident in MBR because of the long SRT which sustained a high biomass concentration of 2-5 times higher than in conventional AS process. This resulted in some nitrogen (as high as 22%) being eliminated through cell synthesis, therefore high concentrations of nitrifying bacteria would contribute to nitrification.

In terms of compliance a comparison between the Darvill and the MBR system is difficult because of the different effluent quality targets, the former being significantly more lenient, in some cases. A better comparison is made in **Section 5** where final water quality and percentage removal can be directly compared.

Discussion: Reliability

In terms of reliability it is evident that neither the Toray nor Norit MBR is operating at the targeted performance level. A number of reasons related to specific contaminant removal have been put forward throughout this report; however, the overriding conclusion was that the process instability contributed to the MBR systems not performing as anticipated.

Biological nutrient removal processes were impacted on by a number of factors including:-

- Variable oxygen concentration in the bioreactor due to the inability of the blowers to consistently achieve the required dissolved oxygen (DO) concentration. Over and under aeration was common place.
- Over aeration of the Toray anoxic tank by over-saturation from the membrane tank recycle. This was not conducive to denitrification.
- The lack of an anaerobic tank in the Toray MBR system was significant in terms of phosphorous removal.
- Sludge concentration (MLSS) could not be maintained and was severely impacted on by operational disruptions and pollution incidents. Reseeding was required on more than one occasion to raise the MLSS concentration to the target 10 000 mg/ℓ. These disruptions appeared to impact negatively on the micro-organism population and possibly also the sludge filterability.
- Operational problems (mechanical breakdowns, power failures, electrical malfunctions) resulted in the membranes requiring maintenance cleaning. This sometimes resulted in outliers being recorded in the permeate water quality, which may not be representative of a plant operating efficiently.

The Darvill WWW also experienced operational difficulties as evidenced by the poor nitrification compliance and suspended solids (SS) removal. Insufficient aeration has been identified as a major concern at the plant with operators unable to maintain a DO of 1.5 to 2 mg/ℓ. This has been put down to inefficiencies experienced with the surface aerators and an ever increasing COD load. Inadequate (< 15 days) SRT is another factor that may be impacting on nitrification, as nitrifying bacteria are slow growing. Other operational problems and poor settling have led to sludge carry-over from the secondary settling tanks (SSTs) resulting in the SS target not being met. The faecal coliform target of 500 CFU/100 ml was only achieved 70% of the time and some effluent figures are extremely high. This figure can be skewed to a certain extent as during high rainfall events the storm dam (balancing dam) can spill leading to raw sewage being recorded at the discharge measuring point. It is, however, important to understand that the spilling storm water flows through a series of maturation ponds beforehand.

It is evident from these results that the MBR systems outperform the Darvill WWW in terms of particulate and micro-organism removal because of the use of membranes for phase separation. In terms of biological nutrient removal the results are more varied and no clear conclusions can be drawn.

5.6 Conclusions

Three methods were used to measure the performance of the MBR pilot plants and the Darvill WWW, namely percentage removal, statistical (student t-test and F-test) and reliability analysis. The percentage removal of contaminants gives an unambiguous and quick assessment of the technologies ability to remove contaminants. The contrast in results is immediately obvious, no more so than in the removal of suspended solids (SS) where the membranes of the MBR provide a physical barrier and remove 99% of SS. The conventional process at Darvill using secondary settling tanks (SSTs) for solids / liquid separation achieves only 71% removal, accentuating some of the problems that are common with SST operation. Percentage removal of contaminants is one of the most common methods of reporting on performance of process technologies and thus made comparison with results obtained on other studies possible.

The t-test and F-test proved ideal for identifying differences in performance of the technologies. The t-test provided a measure of the statistical significance of any difference in performance based on a comparison of the means of the MBR permeate and Darvill final effluent. The F-test highlighted any variability in the process of the technologies. Non-compliance and performance outliers were commonly associated with higher process variability. These basic statistical techniques although ubiquitous in scientific studies are not commonly used in the evaluation of different MBR technologies.

Finally the reliability analysis using the coefficient of reliability (COR) had not previously been used in the evaluation of MBR technology and proved invaluable in assessing the process reliability against set performance targets. It was revealing to note that the targets set for the MBR permeate were difficult to achieve (95% compliance). Excellent average permeate water quality and percentage contaminant removal results could thus be somewhat misleading. The inconsistences in the process (reliability or lack thereof) where highlighted by the reliability analysis. To meet the MBR targets set in this pilot study the design means would have to be stricter for a number of determinants.

A shortcoming of the study was that the effluent water quality targets of the Darvill WWW and the MBR pilot plants are not the same, which made direct comparison of reliability difficult. For example the effluent standard at Darvill for COD is 75 mg/ℓ, and Darvill achieved 85% compliance. The MBR pilots, Toray and Norit achieved only 69 and 40% compliance giving the perception that the Darvill COD process was operating more effectively. However, the performance target for the MBR pilot plants is far stricter at 20 mg/ℓ (COD). The MBR pilot plants achieved 100% compliance at the Darvill 75 mg/ℓ COD standard.

The reliability analysis results should thus be interpreted with this in mind. This cautionary note is, however, not considered a fatal flaw as the assumption is that Umgeni Water attempts to operate the Darvill WWW optimally to obtain the best possible effluent water quality. Comparison of the performance of the Darvill WWW and the MBR pilot plants operating in parallel and utilising the same feedwater is thus considered fair.

CHAPTER 6: PEAKING EVALUATION

6 PEAKING EVALUATION

The city of Pietermaritzburg has separate sewage and drainage systems; however studies (AIM, 2008) have shown that the sewers suffer from high levels of wet weather infiltration. Wet weather flows can reach as high as 3 to 4 times the average dry weather flows. The high levels of infiltration prevalent in the city's sewers potentially represent a barrier to the use of MBR technology at Darvill because the cost of membrane equipment is proportional to the peak hydraulic rate. Any economic advantage of installing MBR would be lost if hydraulic peaks cannot be kept below 2 to 3 times average (Chapman et al., 2006). All wastewater has to pass through the MBR membranes to be considered treated water. As a result MBR's are usually designed with a peaking factor (peak flow to average flow ratio). However, because the removal of permeate through the membrane is a filtration process it is hydraulically constrained by the small pore size. In practice, MBR hydraulic loading is limited to a sustained peak to average flow ratio of approximately 1.5. The membrane may withstand higher flux rates for short durations of up to 8 hours, but sustained fluxes of greater than the 1.5 ratio will stress the membrane and result in premature membrane replacement (Melcer et al., 2004).

Tests therefore needed to be conducted on the MBR systems to determine their capacity to handle wet weather flows, whether these are diurnal or seasonal. Two different peak tests were conducted on the two MBR systems. A 9 day peaking study was conducted on the Toray MBR system that involved running the Toray MBR plant at a peak flux for 24 hr periods, with 24 hour breaks in between. During the off peak periods the plant was run at a reduced flux rate of 20 lmh. The peak flux rate was chosen based on the recommendation of the supplier at a peak factor of 1.25 times the average flux rate. The peak flux rate tested was thus 25 lmh. Due to some operational difficulties, weekends and a CIP the planned sequence of tests could not be followed exactly.

The Norit MBR system was tested using a different approach, as a number of increasing flux (peak) rates were tested, up to and including the maximum flux rate of 70 lmh. The intention was to establish the peak flux capacity of the membrane at high MLSS before proceeding with the 9 day peak tests. Unfortunately following the initial peak flux assessment, the plant could not be restarted due to a SCADA component malfunction and a subsequent membrane rupture. The situation is regrettable as a direct peak test comparison could not be made, however valuable information was still forthcoming from both peak studies.

The peak tests conducted allowed the MBR membrane fouling rates at higher (peak) fluxes to be assessed and to see if the operating pressures (TMP) stayed within the supplier's recommendations.

6.1 Toray MBR

6.1.1 Operating parameters

The supplier recommended operating parameters for the Toray MBR system during the peaking study are specified in **Table 37**. During the peaking study, the Toray MBR system was operated with a filtration cycle of 540 seconds followed by a relaxation period of 60 seconds. The scouring air was kept constant and the recirculation flow rate was adjusted when switching from average flux to peak flux operation.

Table 37: Operating conditions for Toray MBR during peaking study

Mode	Flux (lmh)	Filtration Cycle Time (seconds)	Relaxation Time (seconds)	Scouring Air (Nm^3/h)	Scouring Air Blower (On/Off)	Recirculation Ratio
Average	20 (1.4 m^3/h)	540	60	40	Continuous	3
Peak	25 (1.8 m^3/h)	540	60	40	Continuous	3

A record of the operating parameters such as the flux, TMP and MLSS during the peak test study are provided in **Table 38**.

Table 38: Operating parameters for Toray MBR during peaking study

Description	Hours	Inst. Permeate flow (m^3/h)	Inst. Flux* (lmh)	Initial TMP (mbar)	End TMP (mbar)	TMP loss (mbar)	CIP	Average MLSS (mg/ℓ)
Peak Test 1	24	1.8	25	-65	-125	-60		12848
Reduced Flux	24	1.4	20	-94	-97	-2		12284
Reduced Flux	24	1.4	20	-97	-98	-1		12824
Peak Test 2	12	1.8	25	-98	-151	-53	3 hours NaOCl	12148
Peak Test 2	12	1.8	25	-88	-101	-13		12148
Reduced Flux	72	1.4	20	-71	-74	-3		12140
Peak Test 3	24	1.8	25	-74	-157	-83		12200
Reduced Flux	24	1.4	20	-103	-103	0		12150
Peak Test 4	22	1.8	25	-103	-156	-47		12130

*Instantaneous Flux

6.1.2 Membrane performance

During the nine day peaking study, the permeability of the Toray membrane dropped from 305 lmh/bar (at a flux of 20 lmh) to 167 lmh/bar (at a flux of 25 lmh) just before the completion of the fourth peak test (**Figure 32**). This indicates that the system was not operating in a stable condition.

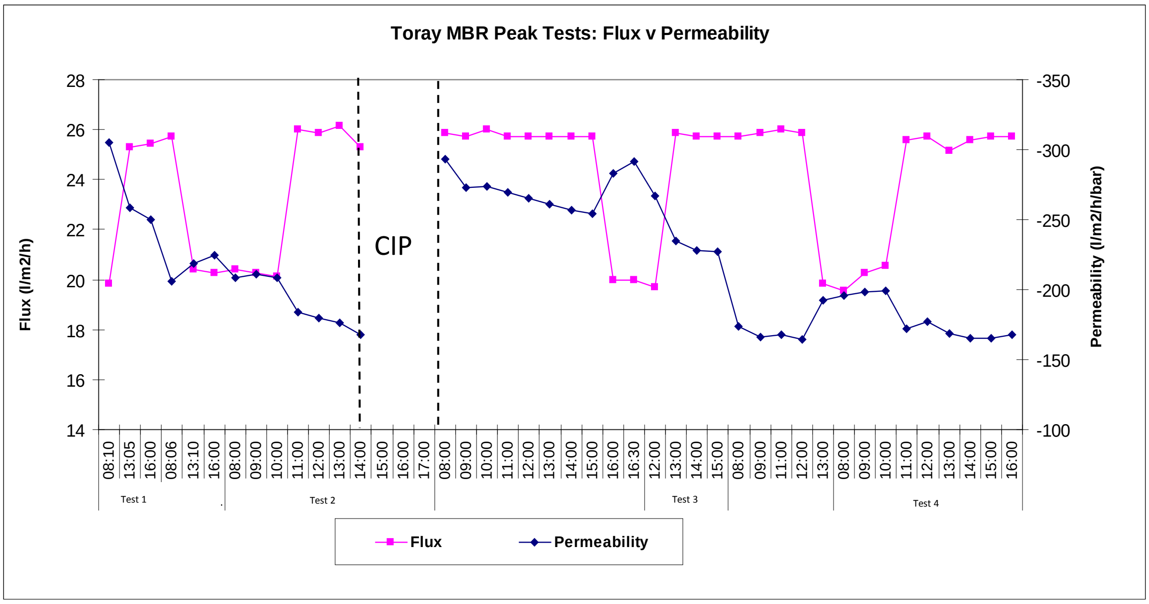

Figure 32: Toray MBR Peak Test Flux and Permeability

In particular it is noted in **Figure 32** that for Peak Test No.3 as the flow was increased to achieve the peak flux, the permeability dropped from 267 lmh/bar to 164 lmh/bar. This rapid drop in permeability during peak flux operation could be attributed to operation beyond the critical flux, the point above which TMP is no longer proportionate to the flux. Once the operation at a reduced flux was resumed, the permeability did not recover back to the normal values until a CIP was done.

Based on the peak test study it was clear that the peak flux of 25 lmh could not be maintained without a rapid drop in permeability resulting in a CIP being required. The predicted average flux rate of 20 lmh was also considered unsustainable and should be lowered to 17 lmh. The predicated peak flux rate based on the operating environment at Darvill WWW is therefore 20 lmh for continued sustainable operation.

6.2 Norit MBR

6.2.1 Operating parameters

The supplier recommended operating parameters for the Norit MBR system during the peaking study are specified in **Table 39**. During the peaking study, the Norit MBR system was operated with a filtration cycle of 420 seconds followed by a permeate backwash of 10 seconds at 8.7 m^3/h. After 16 filtration cycles a drain sequence of the membrane module is performed for 15 seconds, which is then followed by a backwash. The scouring air was kept constant, whereas the recirculation flow rate was adjusted when switching from average flux to peak flux operation.

Table 39: Operating conditions for Norit MBR during peaking study

Mode	Flux (l/m^2/h)	Filtration Cycle Time (seconds)	Backwash Time (seconds)	Backwash Flux (lmh)	Scouring Air (Nm^3/h)	Scouring Air Blower (On/Off)	Recirculation Ratio
Average	45 (1.3 m^{3}h)	420	10	300	13	Continuous	11
Peak 1	55 (1.6 m^{3}h)	420	10	300	13	Continuous	9
Peak 2	60 (1.7 m^{3}h)	420	10	300	13	Continuous	8
Peak 3	65 (1.9 m^{3}h)	420	10	300	13	Continuous	7
Maximum	70 (2.0 m^{3}h)	420	10	300	13	Continuous	7

The daily peaking schedule for the system is shown in **Table 40**.

Table 40: Operating parameters for Norit MBR during peaking study

Description	Hours	Inst. Permeate flow (m^3/h)	Inst. Flux (lmh)	Initial TMP (mbar)	End TMP (mbar)	TMP loss (mbar)	CIP	Average MLSS (mg/ℓ)
Mean Flux	6	1.3	45	0.198	0.191			10844
Peak	43	1.6	55	0.221	0.261	0.04		11272
Peak	24	1.7	60	0.31	0.314	0.003		10848
Maximum	5	2.0	70	0.311	0.443	0.132		10636
Reduced	42	1.7	60	0.319	0.309			9776
Peak	3	1.9	65	0.358	0.348			9192
Reduced	20	1.6	55	0.243	0.3660	0.123		9092
Peak	3	1.9	65	0.291	0.279			9100
Reduced	18	1.6	55	0.255	0.359	0.104		9050

6.2.2 Membrane performance

The flux rate was increased from 45 lmh (1.3 m^3) at 0.18 bar to 55 lmh (1.6 m^3) initially, which resulted in a TMP increase to 0.22 bar. The flux was then increased to 60 lmh (1.74 m^3) and the TMP increased to 0.28 bar. The flux was then increased to the maximum possible flux for the membrane module of 70 lmh (2 m^3). The MLSS concentration at this time was 10636 mg/ℓ just above the target concentration. The flux was kept at 70 lmh for 5.30 hours and then reduced back to 60 lmh at which point the TMP had risen to 0.443 bar. The flux was kept at 60 lmh for the next two days and the TMP was stable at 0.35 bar. As the TMP was stable the flux was increased again, this time to 65 lmh as 70 lmh was considered too high. The flux was reduced and raised between 55 and 65 lmh for the remainder of the test. The permeability remained reasonable constant through this period as did the TMP. A plot of the impact of the peak tests on the permeability in given in **Figure 33.**

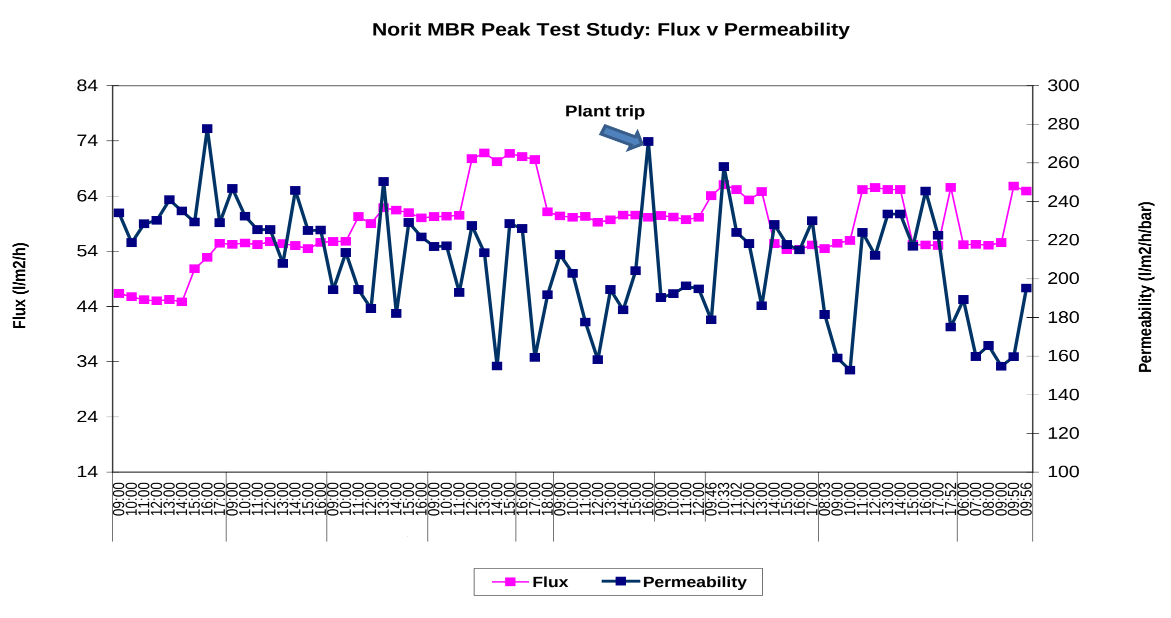

Figure 33: Norit MBR Peak Test Flux and Permeability

A second set of peak tests were started a week later but had to be abandoned because of a high TMP alarm at 0.5 bar. It was later found that a tubular membrane had ruptured during a backwash sequence when a pressure alarm failed. The backpressure and flow exceeded the maximum allowable limits thus damaging the membrane. The pilot plant testing was terminated at this point.

The membrane coped well with the peak tests as evidenced by the relatively stable permeability and predictable TMP increases, which were able to be managed by a controlled drop in flux. The predicted average daily flux for the Norit membrane is 37 lmh and the peak flux 45 lmh or 1.2 times the average daily flux.

To determine the performance of the MBR systems at peak flux, 6-day and 9-day peaking studies were conducted on each MBR system at Point Loma (2009) and Darvill respectively. The operating parameters during the average and peak flux operation were recommended by the manufacturers. During normal operation, all five MBR systems were able to sustain the operation without a significant drop in the permeability. However, a significant difference was observed between submerged and external MBR systems while operating at peak flux. All four submerged MBR systems (US Filter, Puron, Huber, and Toray) showed a temporary decline in the permeability while operating at peak flux whereas no such trend was observed on the external MBR system (Norit). This could be attributed to the operation beyond critical flux for submerged MBR systems while operating at peak flux. For external MBR systems, DeCarolis et al., (2009), points to a relatively higher recirculation flow rate coupled with scouring air that helps to maintain the flux in sub-critical range, even when operating at peak flux.

6.3 Conclusions

The Norit MBR is capable of operation at high flux rates. The peak test assessment confirmed that the Norit membrane can maintain flux rates in excess of 60 lmh for extended periods of time. The Norit MBR should therefore comfortably cope with high flows associated with wastewater peaks or storm water inflows. The installation of external Norit MBRs may therefore pose advantages for WWW impacted on by variable flow associated with peaks.

Where flow is less variable and peak flows are not high, the Toray MBR (with limited peak flow capability) may be more appropriate because of its reduced energy requirement and commensurate lower operating costs.

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

This final section reviews the four major project objectives (listed below) and discusses the results and outcomes.

The main objectives of this research were:

(1) To compare the relative performance of two MBR configurations operated in parallel with the Darvill WWW in terms of the following:

a) Permeate flux (sustainable flux rate)

b) Maintenance requirements (backwash/relaxation frequency, cleaning in place (CIP)

c) Quantification of the treatment efficacy by measuring the removal efficiencies of specific pollutants

(2) To compare the relative performance of two MBR pilot plants with the conventional treatment process used at Darvill WWW in terms of effluent quality and process reliability.

(3) Establish the peak sustainable flux rates of the membranes.

Objective 1

Based on the operating experience and recorded MBR performance the predicted average flux for the submerged Toray MBR system is 1.2 m^3/h (17 lmh), whereas that for the external Norit MBR system is predicted at 1.1 m^3/h (37.5 lmh). The predicted peak flux for the Toray membrane was 1.4 m^3/h (20 lmh) whereas for the Norit external membrane it was 1.3 m^3/h (45 lmh). The predicted cleaning frequency for the Toray MBR is 5-6 weeks and 7-8 weeks for the Norit MBR. The calculated sustainable flux rates are less than those expected and reported by the membrane manufactures and the required cleaning is more frequent. It was concluded that the industrial component of the influent sewage was having a marked effect on membrane flux and permeability.

The flux rates achieved for the external Norit tubular membrane are far higher than those for the submerged Toray FS membrane; however, the energy usage is higher in the Norit MBR because of the need to maintain a high cross-flow velocity to avoid fouling.

Membrane fouling was observed to increase as operating flux increased as was evidenced by the reduction in the calculated runtimes between cleaning intervals. For example in the Toray MBR, cleaning intervals decreased with increasing flux, as follows: 90 days at 7 lmh, and 21 days during operation at 15 lmh and 14 days at 20 lmh. The primary reason for the increased fouling rate at higher flux rates is due to an increase in mass loading of solid, organic and microbiological contaminants. The recovery of permeability following chemical cleans with sodium hypochlorite and citric acid is, however, evidence of these foulants being removed.

The MBR pilot plants out-perform the conventional activated sludge and secondary clarification process operated on the Darvill WWW for all determinants with the exception of phosphate removal (SRP). A summary of MBR results indicated that the MBRs achieved superior results regardless of influent conditions:-

- Turbidity / Suspended Solids (99% removal)
- Nitrification (conversion of ammonium to nitrate) of 90-95%
- COD removal efficiency of 92-95%
- Faecal (E.Coli) and total coliform removal of 98-99%
- Coliphage (viruses) removal of 95-99%

The exception was with phosphate removal, where the Darvill effluent was significantly better than the Toray MBR. As previously explained this was due to the Toray MBR not having an anaerobic zone and hence its phosphate removal process was not effective. The Norit MBR showed excellent phosphate removal as a result of the operation of an anaerobic zone.

Objective 2

A number of methods were used to measure the performance of the MBR pilot plants and the Darvill WWW, namely percentage removal, statistical (student t-test and F-test) and reliability analysis. The percentage removal of contaminants gives an unambiguous and quick assessment of the technologies ability to remove contaminants. The contrast in results between the MBRs and Darvill WWW is immediately obvious, no more so than in the removal of suspended solids (SS) where the membranes of the MBR provide a physical barrier and remove 99% of SS. The conventional process at Darvill using secondary settling tanks (SSTs) for solids / liquid separation achieves only 71% removal, accentuating some of the problems that are common with SST operation.

The t-test and F-test proved ideal for identifying differences in performance of the technologies. The t-test provided a measure of the statistical significance of any difference in performance based on a comparison of the means of the MBR permeate and Darvill final effluent. The F-test highlighted any variability in the process of the technologies. Non-compliance and performance outliers were commonly associated with higher process variability.

In terms of reliability it is evident that neither the Toray nor Norit MBR is operating at the targeted performance level. A number of reasons related to specific contaminant removal have been put forward throughout this report; however, the overriding conclusion was that the process instability due to plant disruptions contributed to the MBR systems not performing as anticipated. To meet the MBR targets set in this pilot study the design means would have to be stricter for a number of determinants.

The Darvill WWW also experienced operational difficulties as evidenced by the poor nitrification compliance and suspended solids (SS) removal. The increase in the organic load has put a strain on the capacity of the plant to biologically treat and remove nutrients, especially nitrogen in the form of ammonia, from the wastewater. Operational problems and poor settling have led to sludge carry-over from the secondary settling tanks (SSTs) resulting in the SS target not being met. The faecal coliform target of 500 CFU/100 ml was only achieved 70% of the time and some effluent figures are extremely high.

Objective 3

The Toray system showed a temporary drop in permeability during peak flux operation, which could be attributed to the operation beyond critical flux at peak flows. No such trend was observed for the Norit system. During the peaking study conducted, no irreversible fouling was observed on both of the systems

9.2 Recommendations

Darvill WWW is a large strategically important WWW, as it is the only WWW servicing Pietermaritzburg, the capital city of KwaZulu-Natal. From a socio-political perspective it is thus a high profile WWW, under scrutiny from the DWS and NGO’s such as DUCT (Duzi Umgeni Conservation Trust). Darvill WWW discharges into the Msunduzi River, famous for the Duzi canoe marathon, and feeds Inanda Dam, Durban’s largest water resource. Poor effluent quality from Darvill WWW reflects poorly on Umgeni Water and contributes to eutrophication at Inanda Dam, as a result of increasing nutrient loads. Further eutrophication may result in a deterioration of raw water quality and has the potential to lead to potable water treatment problems and escalating treatment costs. The superior effluent quality achievable by MBR would result in the current discharge standards being exceeded, thus leading to an improvement of the current situation and a number of socio-economic benefits. These benefits are considered worth the additional cost of MBR.

It is recommended that MBR be installed at Darvill WWW, as it would resolve the WWW treatment problems and produce a superior effluent quality that would be compliant with the legislated discharge standards.

The Norit MBR is recommended ahead of the Toray MBR, as this research has shown it to have a number of advantages including:

- Longer cleaning frequency cycles,
- Higher sustainable flux rates,
- Higher sustainable peak flux rates,
- Easier maintenance, as membrane modules are external of the bioreactor.

There are, however, limitations to this recommendation as the operating cost of the two MBRs was not established in this study.

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Annexure A

Process Flow Diagrams

a) Norit Demonstration Plant Process Flow Diagram

b) Toray Demonstration Plant Process Flow Diagram

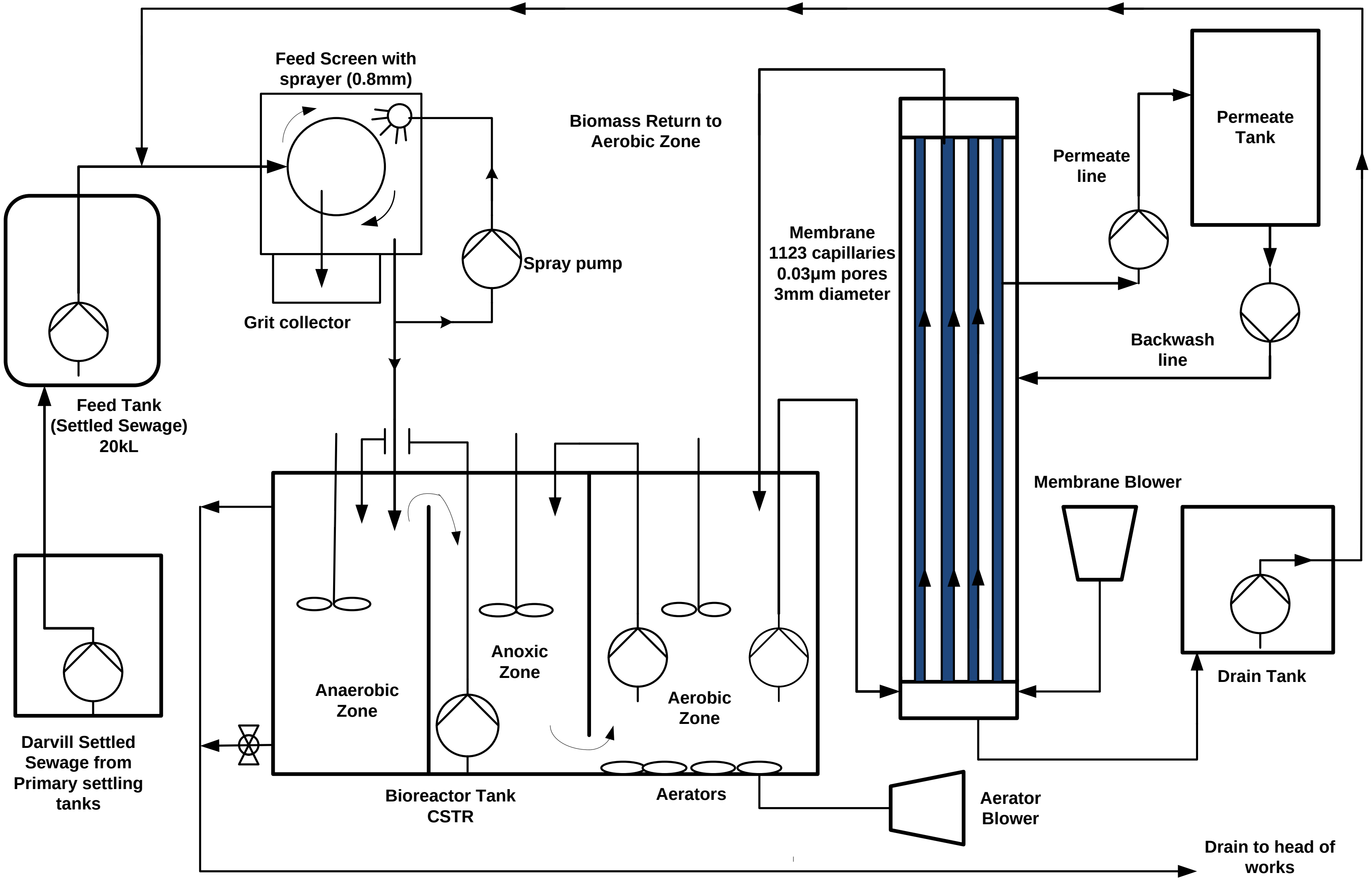

Figure 34: Norit MBR Process Flow Diagram

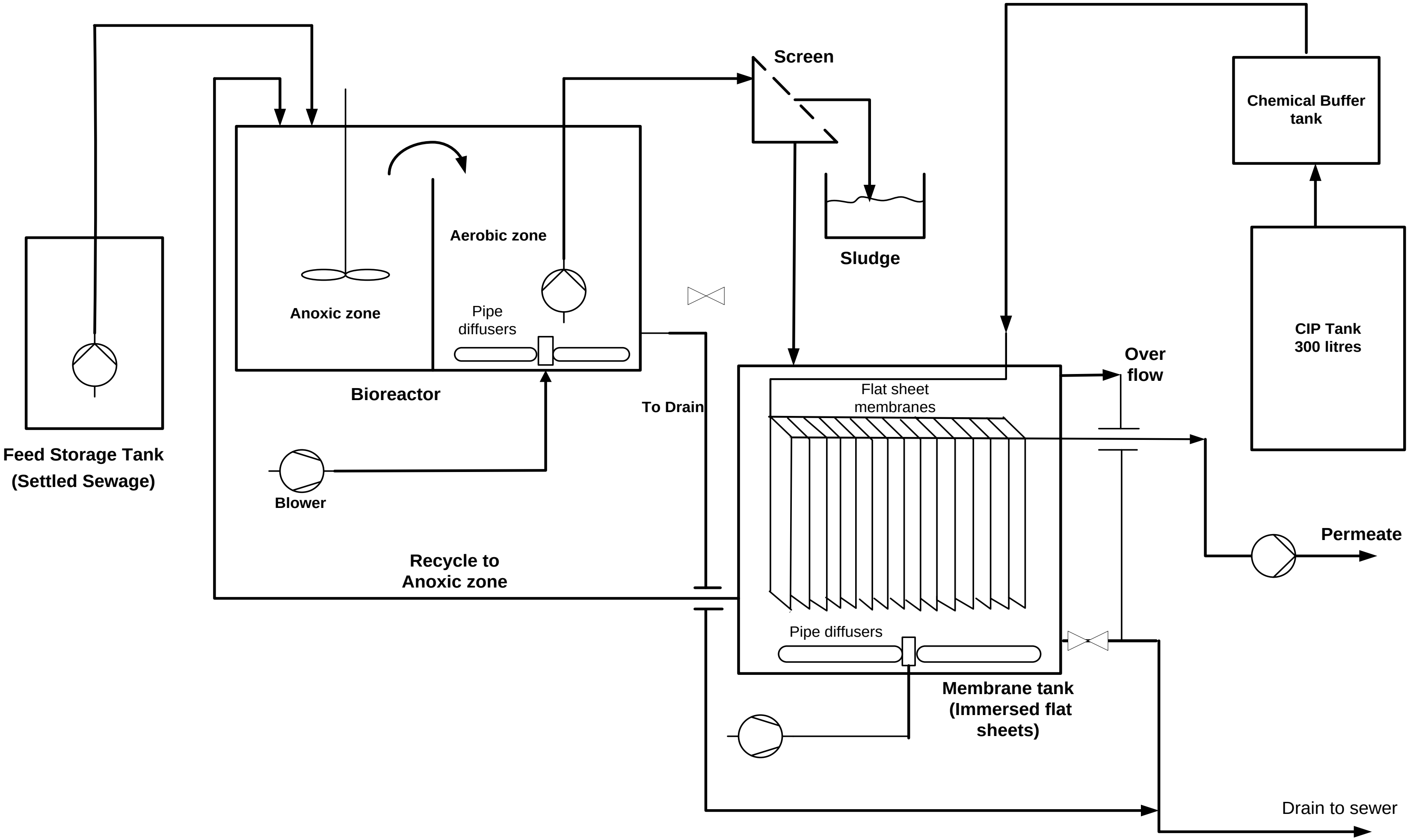

Figure 35: Toray MBR Process Flow Diagram

Annexure B

List of Analytical Laboratory Instrumentation

Table 41: 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

<u>Other:</u>

Effluent turbidity is another key parameter in reclamation applications. Title 22 in California requires 0.2 NTU for membrane-filtered effluent:

Ref: Membrane Basics for WW Treatment: Neethling JB, Clark, D and Pellegrin, ML. 2009. Supplier File

Annexure C

a) Cumulative Frequency Distribution (CFD) Plots

b) Empirical Distribution Plots

Cumulative Frequency Distribution (CFD) Plots

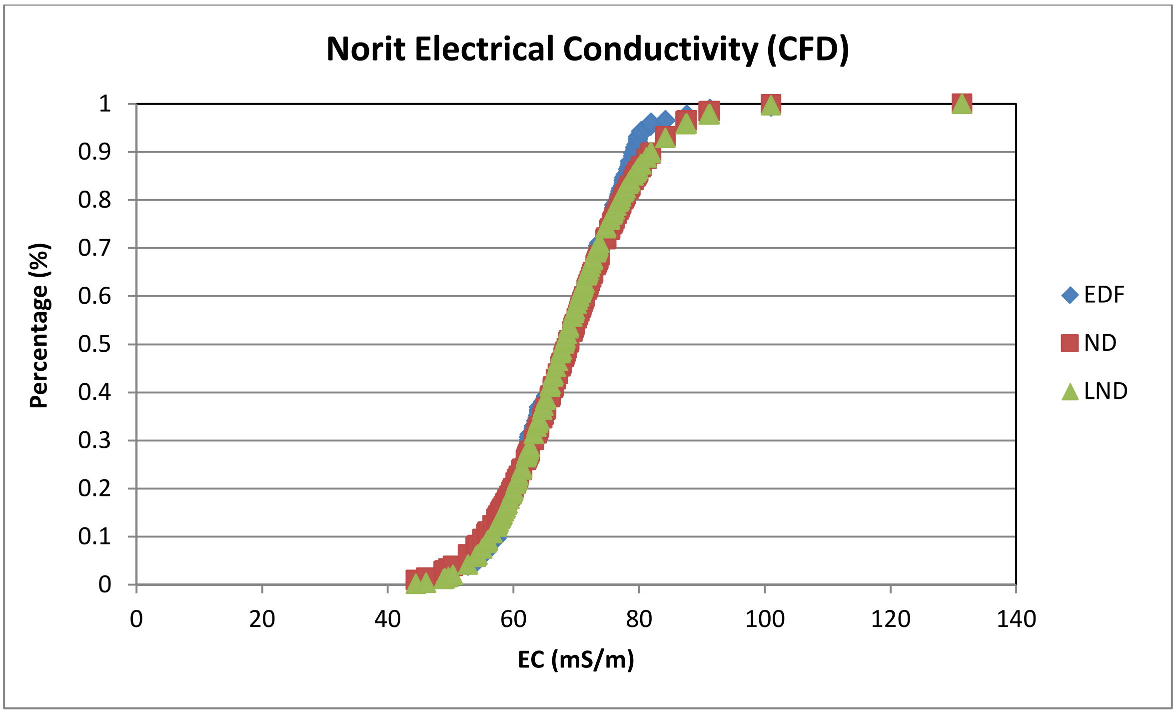

Figure 36: Norit Permeate Electively Conductivity (EC) Cumulative Distribution

(EC is both normally and log-normally distributed)

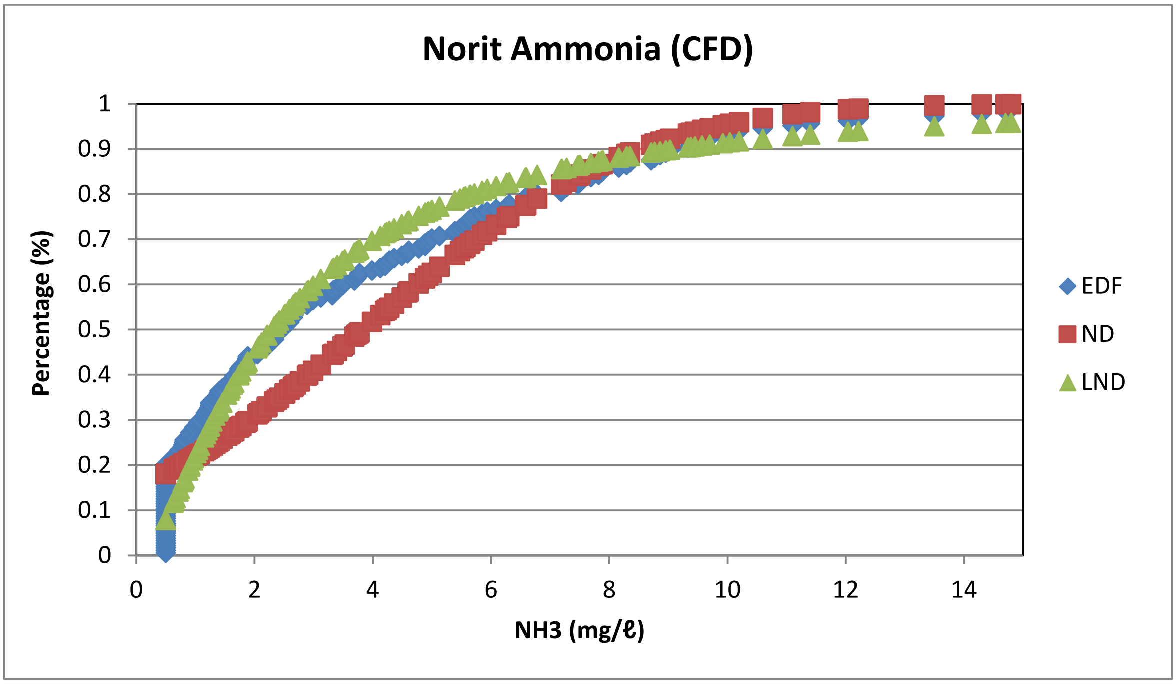

Figure 37: Norit Permeate Ammonia (NH_3) Cumulative Distribution

(NH_3 not normally or log-normally distributed)

Empirical Distribution Plots

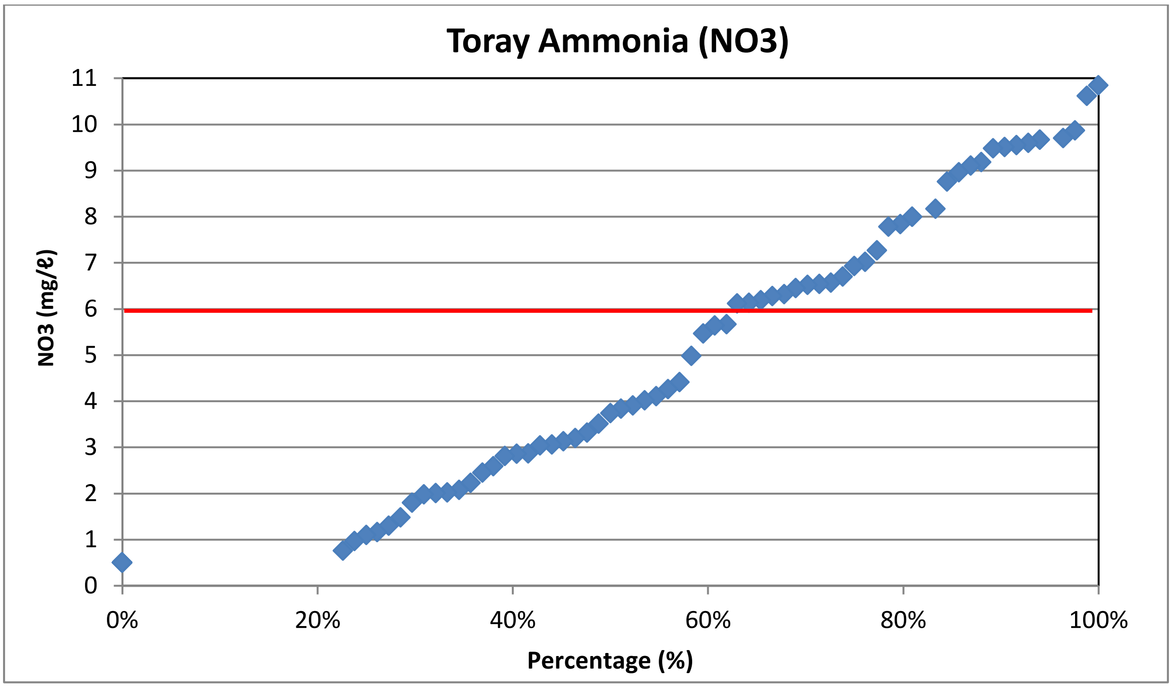

Figure 38: Toray Permeate Nitrate (NO_3) Empirical Distribution

(Ammonia discharge standard of 6 mg/ℓ is achieved 64% of the time)

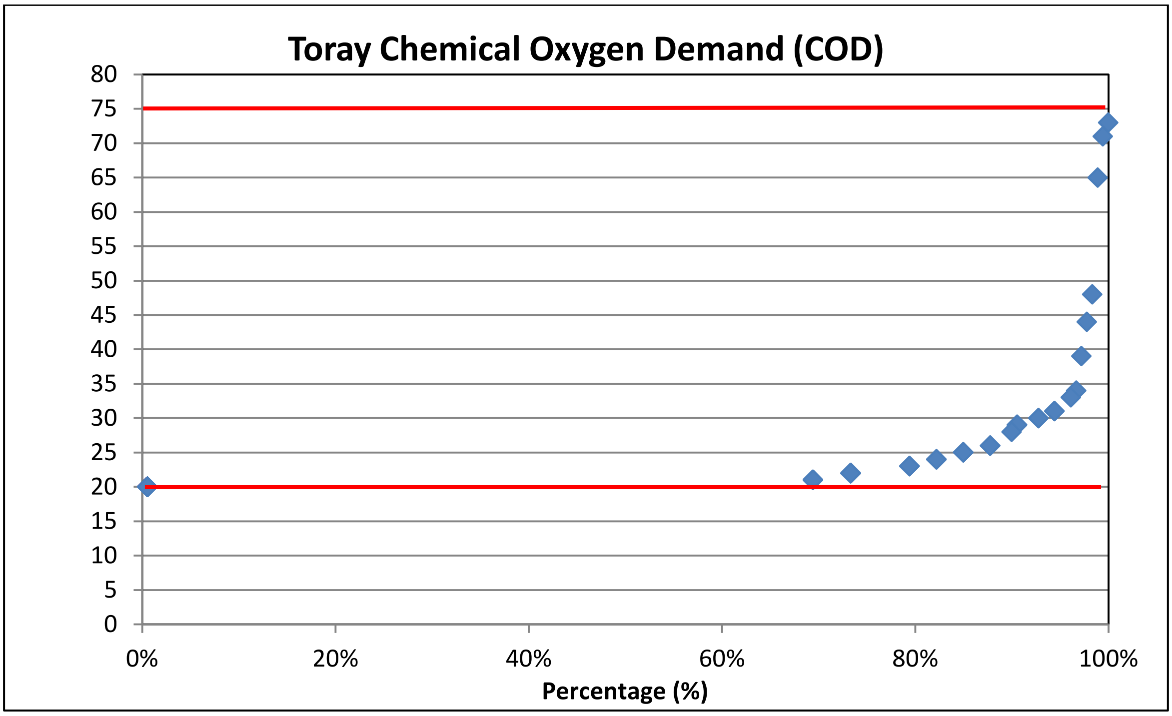

Figure 39: Toray Permeate Chemical Oxygen Demand (COD) Empirical Distribution

(The Darvill COD discharge standard of 75 mg/ℓ is achieved 100% of the time, and the MBR permeate effluent target of 20 mg/ℓ is achieved 69% of the time.)

Annexure D

Coefficient of Reliability

Expected percentage of compliance calculations:-

$$Z_{1-\alpha} = \frac{\ln X_S - \left[\ln m_x \quad - \quad \frac{1}{2}\ \ln(CV^2 + 1)\right]}{\sqrt{\ln(CV^2 + 1}}$$

Where:
m_x = mean effluent concentration (mg/ℓ),
X_s = specified discharge standard
CV = Coefficient of variation

$$CV = \frac{s_x}{m_x}$$

Where: s_x = standard deviation

Using the Norit turbidity as an example the workings are as follows:

$m_x = 0.44$
$X_s = 1$

$$CV = \frac{s_x}{m_x}$$

CV = 0.3 / 0.44 = 0.72

$Z_{1-\alpha}$ = ln 1 – (ln 0.44 – 0.5 ln $(0.72^2 + 1)$ / √ln $(0.72^2 + 1)$
= 0 – ((-0.82 – (0.5 x 0.42)) / √0.42
= 0 – (1.03) / 0.64
= 1.61

$Z_{1-\alpha}$ = 1.61, and from standard normal variate tables the percentage compliance is 95%.

Determination of Design Mean

Coefficient of Reliability (COR) calculation

$m_x = (COR)X_s$

Where m_x = mean effluent concentration (design or operational value)

X_s = specified discharge standard

COR = coefficient of reliability

The coefficient of reliability (COR) is calculated using the following equation:

$$\text{COR} = \sqrt{CV^2 + 1} \text{ x exp} \{-Z_{1-\alpha} \sqrt{\ln(CV^2 + 1.}\}$$

Where: CV = coefficient of variance (standard deviation divided by the mean)

$Z_{1-\alpha}$ = standardized normal variate (obtained from the standard normal variate tables) corresponding to the probability of no exceedance at a confidence threshold of $(1-\alpha)$

α = significance level

COR $= \surd\ 0.72^2 + 1 \text{ x e } \{-1.645 \surd\ln (0.72^2 +1)\}$

$= 1.23 \text{ x e } \{ -1.645 \text{ x } 0.65\}$

$= 1.23 \text{ x } 0.34$

$= 0.42$

From the COR obtained, it is possible to determine the design concentrations that would be required to achieve the discharge standards, therefore:-

m_x $= (\text{COR})X_s$

$= 0.42 \text{ x } 1$

$= 0.42$

The design mean of 0.42 NTU will be required to achieve 95% compliance if the discharge standard of 1 NTU.

Annexure E

MBR Pilot Plant Operational Records

Toray Membrane Operational Performance Record

The membranes were operated at a start-up flux of 7 lmh (0.5 m^3/h) for 720 hours (**Figure 14**). At this point the bioreactor water level probe malfunctioned resulting in no influent flow into the bioreactor and the plant was shut down. Normal operation was resumed in Week 31. After 216 hours of operation at 7 lmh the plant had to be shut down following a pollution incident over the Christmas holidays which resulted in soapy foaming. The pollution killed the biomass and the bioreactor was reseeded with activated sludge in Week 34 and filtration was resumed at 7 lmh. Following a further 216 hours of operation another industrial pollution incident occurred. The pollution killed the biomass and MLSS concentration dropped to 500 mg/ℓ. The plant was reseeded with activated sludge and the flux rate was increased from 7 lmh to 15 lmh (1 m^3/h) in Week 36. After 192 hours of operation a chemical clean was performed in Week 38, in response to another pollution incident. Foaming and a drop in the MLSS to 1000 mg/ℓ were a consequence of the pollution, which is shown below (**Photo 1**)

Figure 40: Pollution incident in Toray Bioreactor

The target operating TMP specified by the supplier is in the -30 to -130 mbar range. The membranes continued to be operated at 15 lmh up until Week 41 when another CIP was required after 336 hours of operation. The TMP as this time was -60.6 mbar. Following the CIP, the TMP decreased to -13.5 mbar, and operation at 15 lmh was continued. Two days afterwards the flux rate was increased to 20 lmh (1.4 m^3/h). The TMP increased from -40.2 to -180 mbar during the next 168 hours of operation at this high flux rate. At a TMP of -180 mbar the pilot plant went into alarm and had to be shut down so that another CIP could be undertaken. Filtration was resumed but only for a few days as in Week 43 the membrane tank blower seized and the plant had to be shut down so repairs could be undertaken. A number of attempts were made to restart the plant but the blower kept tripping. The problem was eventually fixed and the plant restarted in Week 45. Filtration continued at 20 lmh for the next 264 hours and was then reduced to 17 lmh in response to rising TMP. In this period the TMP increased from -39.6 to -153.5 mbar. The reduction in flux rate had no significant impact on reducing the TMP which continued to rise to -160.6 mbar until the plant went into alarm overnight. A CIP was undertaken on the membranes in Week 47. The plant was operated at a flux rate of 17 lmh for the next 192 hours and in Week 48 the plant was seeded with RAS. During the operating period, the TMP increased from -46.3 to -166.3 mbar at which point the plant went into alarm, requiring a CIP be undertaken. Filtration was resumed in Week 49 and during this operating period, the TMP increased from -38.5 to -141.1 mbar after 432 hours of operation. During this period the activated sludge in the bioreactor was spiked with RAS in Week 51 in an attempt to increase the MLSS concentration. This was achieved and the MLSS concentration was increased from 6688 to 11136 mg/ℓ. A maintenance clean was performed in Week 52 and on resumption of filtration the flux rate was increased to 20 lmh. During the next 168 hours of operation the TMP increased minimally from -31.8 to -58.9 mbar and the system was therefore considered relatively stable. The MLSS concentration during this period was within the manufactures target range of 10 000 – 13 000 mg/ℓ and this is believed to have resulted in the improved membrane performance. As stability had been achieved in the operation of the MBR system and the MLSS concentration was within the target range it was considered an appropriate time to conduct the peaking experiments. The results of the peaking experiment are discussed in **Chapter 6.**

Norit Membrane Operational Performance Record

Flux was initially kept very low at 25 lmh (0.75 m^3/h) during the first few weeks of operation on the instructions of the supplier in order to avoid rapid fouling of the membrane. In Week 3 the flux was increased to 35 lmh (1 m^3/h). Shortly afterwards industrial pollution in the plant influent killed the biomass in the bioreactor. The pollution resulted in severe foaming and turned the brown sludge a transparent grey colour. The incident caused the TMP to rise overnight from 0.13 to 0.3 bar. The plant was stopped and the bioreactor, permeate tank and drain tank were all drained manually and flushed with municipal water.

The plant could not be operated for any length of time from Week 4 to 8, because of numerous operational problems. After resolving some issues the plant was started again in Week 9 at a flux of 35 lmh. The plant was operated for 360 hours from Week 9 to 11, until a sudden increase in TMP beyond 0.5 bar tripped the plant. A CIP was performed soaking the membranes in sodium hypochlorite (NaOCl) for 2 hours and then following a rinse soaking them in a 2% citric acid solution overnight. The plant was restarted the next day at 35 lmh at a reduced TMP of 0.1 bar. The plant was operated for 288 hours from the Week 11 to 12 at which point is was stopped so that a broken elbow in the raw wastewater feed line could be repaired. During this period the flux rate was steadily increased from 35 lmh to 40 lmh (1.16 m^3/h).

From Week 13 the plant was operated, with minor stoppages for 1272 hours to Week 21. At this point the TMP exceeded 0.5 bar and the plant was stopped. A CIP was performed overnight which reduced the TMP to 0.21 bar and the plant restarted a day later at a flux rate of 35 lmh. A week later after 144 hours of operation the flux was increased to 37.5 lmh (1.13m^3/h). In Week 22 the plant tripped due to high TMP and a CIP was performed (NaOCl soak) before resuming filtration. Shortly afterwards a power outage at Darvill resulted in the plant tripping over the weekend, which resulted in sludge being left standing in the membrane vessel overnight. Flirtation was resumed after the weekend at a relatively high TMP of 0.37 bar.

The plant was operated for a further 432 hours to Week 26 at which point the TMP had reached 0.43 bar. At this time the plant tripped due to a PLC failure. The problem with the PLC required replacement parts to be ordered and imported from Holland which resulted in the plant being shut down and offline for over 2 months. Attempts to get the plant running in Week 31 were short lived and the PLC failed again. Because the plant had been standing for some time (with potable water in membrane) a CIP was performed before start-up once all the problems had been resolved. The CIP involved two NaOCl soaks and drain sequences, one overnight NaOCl soak and an 8 hour citric acid soak, completed with flushing and draining the membranes with potable water. Operation was resumed in Week 35 at a flux of 40 lmh at a TMP of 0.16 bar. During the next 96 hours of operation the TMP increased to 0.3 bar as a result of a suspected pollution incident. The permeate flux rate was dropped back to 35 lmh as a precaution in Week 39. The plant continued to operate, with the flux rates being raised and lowered in response to operation conditions and increases in the TMP. The flux rate was controlled between 30 – 42 lmh during this period of 1008 hours of operation from Week 35 to 41. At TMP approaching 0.5 bar, the plant was shut down so that a CIP could be performed.

The shutdown was used as an opportunity to clean the plant drum screen with a high pressure hose as this had been getting clogged with algae and grit. The drum screen was not only used to filter the raw wastewater influent, but the biomass from the membrane following a drain sequence was also fed through the drum screen. The clogging of the drum screen was resulting in overflow to waste, which was thought to be potentially resulting in a loss of solids (biomass).

In Week 42 the plant was restarted with a flux of 30 lmh (TMP= 0.12 bar) and run for 432 hours until the TMP reached 0.47 bar in Week 44. The plant was stopped for a CIP to be performed, following which filtration was resumed at a flux of 35 lmh. A few days later the plant had to be shut down following a valve failure on the raw wastewater feed line. The valve stayed open and continuously fed raw wastewater into the bioreactor displacing all the sludge. The bioreactor had to be reseeded with activated sludge from the Darvill ASTs. In Week 45 the TMP rose to 0.47 bar and after a CIP (2 hour NaOCl) was performed it dropped to 0.27 bar. During the next 264 hours of operation the TMP rose from 0.27 bar to 0.43 bar, at which point another CIP was required to drop the TMP back down to 0.07 bar. On resumption of filtration in Week 47 the permeate flux was set at 37.5 lmh, raised to 40 lmh two weeks later and increased further to 45 lmh (1.3 m^3h^{-1}) a week after that. Filtration continued at this flux rate until Week 51. For the period of 672 hours of operation the TMP had increased from 0.07 bar to 0.36 bar.

A MLSS above 10000 mg/ℓ representative of a true MBR system was required to perform the peak test analysis; hence in Week 52 the bioreactor was reseeded with RAS from the Darvill WWW. As the Norit rental period was running out and the target MLSS concentrations had not yet been achieved or maintained the project team decided on this course of action. The RAS seeding increased the MLSS concentration from 4568 mg/ℓ to 6560 mg/ℓ. The plant was restarted at 35 lmh and at a TMP of 0.28 bar. The following day the bioreactor was spiked with more RAS and this managed to increase the MLSS to 7350 mg/ℓ. The flux was increased to 45 lmh four days later and filtration continued with the TMP rising gradually to 0.33 bar. Over the next two days an I/O (input/output) module was faulty and the plant tripped. The I/O module was replaced and filtration continued at 45 lmh (TMP = 0.22 bar) for five days after which the flux was increased to 47 lmh (1.3 m^3/h). At this point the bioreactor was again spiked with RAS and this brought the MLSS to 10844 mg/ℓ, above the target MLSS concentration and high enough to undertake the peak tests. The results of the peaking experiment are discussed in **Chapter 6**.

Annexure F

MBR Pilot Plant Operating Experience

MBR PILOT PLANT OPERATING EXPERIENCE

Toray

The Toray MBR pilot plant was fully automated and required very little operator attention. The plant components could be operated either in manual or automatic mode via a very simple touch screen. Remote access was made available so that the plants could be operated from the operators PC. The pilot system required operator attention for sludge wasting since the sludge wasting had to be done manually. Since there was no flow meter on the sludge wasting line, the sludge volume had to be measured manually.

The feed line to the plant passed through an inline rotameter which got clogged a few times. This reduced the feed flow significantly resulting in the bioreactor level dropping, as the plant was still in filtration mode. As a result, the feed pump had to be stopped, and the rotameter had to be cleaned manually to restore the desired flow rate.

The plant was relatively new and in excellent condition and thus very little went wrong mechanically during the operating period, with only two major mechanical failures occurring. The membrane tank blower had to be refurbished as did the permeate pump. Both these incidents caused operational downtime, but in the long run were not significant. The drum screen required adjustment from time to time and cleaning when required.

The blower in the biological reactor was problematic and the operators were unable to adjust the aeration accordingly to maintain the target 1–2 mg/ℓ DO level in the aerobic tank. Although a variable speed drive (VSD) the blower seemed incorrectly sized for the size of tank and would generally over aerate. It had to be continually adjusted and the operators had to take DO readings manually in order to do this as the DO probe that was linked to it provided incorrect readings.

Norit

The Norit MBR demonstration plant was fully automated but required operator attention for sludge wasting, which was not a concern as no sludge was wasted. The plant could be operated using a touch screen on site, but this was somewhat difficult as the screen was damaged. Fortunately remote access allowed the operators to operate the plant from their PC.

The plant had been used previously at a trial in Singapore where it was shipped from. The age of the plant was not known but it was visibly run down to some extent, with rust in places. There were a number of mechanical failures and components that had to be replaced, including a new compressor. The original compressor, used to operate the pneumatic valves on the system caused extensive problems for a number of months before it was replaced.

The most frustrating thing for the operators was the continuous tripping of the plant as a result of PLC I/O problems. A number of analogue components had to be imported from Norit in Holland to resolve the problems.

In summary there were operational and mechanical issues almost on a daily basis with the plant and this made the operators' task very difficult. When operating without problems the Norit MBR system worked well as is evidenced by the results. The age of the plant was the problem and not the Norit membrane technology.

Conclusions

A number of conclusions and recommendations can be drawn from the experience of operating these pilot plants that may prove useful to future researchers and also be transferable to the operation of new full-scale MBR plants. Some of the more salient experiences and recommendations include:-

- The pilot plants would have been difficult to operate without full automation. Process control using the on-site PLC was simple and effective. Remote access via the internet added flexibility of operation, especially on weekends and public holidays. It also allowed specialized input and advice to process issues and speedy resolution of problems. The SCADA system allowed accurate problem diagnosis and fault finding which avoided excessive downtime.
- On-line instrumentation saved time and provided back-up to routine manual measurements. Some instrumentation was, however, not without its problems and the submerged instrumentation needed cleaning and calibration every few months. The on-line permeate turbidity meter also needed calibrating every so often, but this was not problematic as the out of range readings were easily identifiable. Malfunctioning of the water level depth probes (sonar) are a concern and require a backup system or manual checking. Incorrect level readings resulted on separate occasions in the bioreactor being drained of all MLSS and the settled sewage feed tank overflowing.

- One of the biggest problems was the availability of instrumentation technicians to ensure a high level of plant availability. No formal arrangements had been made in this regard with Umgeni Water and thus any assistance requested was subject to approval and availability of the technicians. As they were naturally busy and the pilot plants were not a priority and this resulted in unnecessary delays.
- The procurement of spares, especially replacement mechanical equipment caused delays. If possible back-up compressors, feed and permeate pumps should be sourced prior to starting pilot plant trials.
- As previously stated the performance (sustainable flux rate) of both MBR's was lower than anticipated by the manufacturers. The 10% industrial component of the feed effluent appeared to have a marked effect on flux rate and the flux rates normally associated with a purely domestic sewage could not be achieved. It would thus be advisable for any green field projects with a mixed effluent to conduct pilot trials to establish sustainable flux rates, otherwise there may be a risk of the full-scale plant being under-designed.

Annexure G

Cost Estimate

Cost Estimate

The cost estimate proposal is based on the retrofitting of Darvill WWW and changing the operation of the existing activated sludge basins into a membrane bioreactor. This would involve the installation of submerged membrane modules and diffused aeration. Currently the plant uses surface aerators.

The design of the secondary settling process stage is based on the assumption that the flow will be balanced prior to the biological treatment phase and that the forward flow will be limited to 110% of the Average Dry Weather Flow (ADWF) i.e. 70 Mℓ/day.

Capital Cost Estimate

The MBR process sizing was calculated using Koch Puron software and 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 Ultra-filtration (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 (HF) Puron membranes are generally higher and a gross flux rate of 25 lmh and a net flux of21 lmh was selected.

The process design was done using Koch Puron HF MBR technology as this was the only MBR software that could be readily obtained at the time. As the majority of MBRs provide high quality permeate water the use of an alternative MBR technology was not considered a fatal flaw in the cost estimation. As is evident in the operating cost estimate (**Section 8.2**) that follows, HF MBR technology uses less energy than FS (Toray) and Multi-tube (Norit) MBR technology. Energy usage is a critical factor when evaluating MBR against conventional processes, and thus it was considered advantageous to use a HF MBR for the cost comparison.

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 off-line 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 m^2;
- 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 m^2 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 Nm^3/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 a 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 $Nm^3/(m^2h)$.

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 the 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 all possible upgrade options and have not been included.

The breakdown of capital costs for the Membrane Bioreactor installation at Darvill WWW is given in **Table 42**.

Table 42: Capital cost estimate for retrofitting Darvill AS with MBR

	MBR
Plant Size (m3/day)	120 000
CAPEX	MBR
Total Civils	R 31 528 875
Total Mechanical	R 222 459 780
Ancillary Equipment	R 27 599 040
Electrical & Instrumentation	R 10 650 000
Sub-Total	R 292 237 695
P&Gs (25%)	R 73 059 424
Sub-Total	R 365 297 119
Contingencies (10%)	R 36 529 712
Total (excl. VAT)	**R 401 826 831**

Operating Cost Estimate

An evaluation of energy consumption was not conducted in this project as it was not part of the scope and because of the limitations of measuring energy usage at a pilot scale. These limitations were raised in **Chapter 3** and relate largely to scale-up issues, the usage at pilot scale not being representative of usage at full-scale where economies of scale and process optimisation plays an important role. There is; however, an abundance of research that is dedicated to this topic.

An example of energy usage at a number of full-scale plants is provided in **Table 43**. As reported by Krzeminski et al. (2013) the energy usage of combined MBR and CASP and stand-alone MBR plants was measured over an extended period. Different MBR technologies are used including submerged FS (Toray), HF (Zenon) and sidestream tubular (Norit) membranes. The study thus provides a valuable insight into the usage of the Toray and Norit MBR technologies at full-scale.

The average specific energy consumption of the three plants (technologies) was surprisingly similar. As expected the lowest average energy consumption was obtained when using the HF membranes at Varsseveld. It is widely reported that HF MBR is the most energy efficient. The tubular Norit MBR had marginal lower energy consumption than the FS MBR, which is unexpected as sidestream MBR technology is generally more energy intensive (Judd, 2011). The energy comparison between the MBRs was thus inconclusive based on these results and further investigation is required. It must not be forgotten that because sidestream MBRs can apply higher fluxes, they need fewer membranes than submerged MBRs and thus require lower capital costs.

Table 43: Full scale MBR plant energy usage comparison

Location	**Heenvliet MBR**	**Varsseveld MBR**	**Terneuzen MBR**
MBR Technology	Toray (FS)	Zenon (HF)	Norit (Multi-Tube)
Period of study	2008–2010	2005–2010	2010
Design dry weather flow [m^3/month]	36,000	180,000	288,000
Treated flow [m^3/month]	27,826	132,054	169,984
Monthly power requirement [kWh]			
Max	33,869	146,051	166,332
Average	22,700	110,486	154,636
Min	14,165	58,408	146,581
Daily power requirement [kWh]	1,788	N.A.	5,888
Yearly power requirement [kWh]	227,001	1,325,833	N.A.
Specific energy consumption [kWh/m^3]			
Max	1.82	1.44	1.28
Average	1.06	0.84	0.97
Min	0.77	0.60	0.76

Based on this study the municipal MBRs consume on average 0.8–1.1 kWh/m3 (average 0.95 kWh/m^3) and this can be used for comparative purposes with a CASP. At a current bulk electricity tariff of R1.20 kWh (2016) for a 120 Mℓ/day capacity plant this would equate to an operating cost of:-

114 000 kWh/day x R1.2 = R136 800 per day or R49 million/annum.

The equivalent energy cost for an upgraded conventional activated sludge plant at Darvill would be R36 million /annum.

Conclusion

Upgrading the Darvill WWW with conventional activated sludge processes proved to be more economical from a CAPEX and OPEX perspective in studies completed by GOBA (Pty) Ltd, (2013) and therefore MBR was not recommended.

It should be noted, however, that a fair comparison of MBR systems with CAS systems is only possible when similar effluent quality is produced. Meaning, a direct comparison between MBR and even CAS with sand filtration is not appropriate (Krzeminski et al., 2013)