WASTEWATER RECLAMATION FOR POTABLE REUSE

VOLUME 1: EVALUATION OF MEMBRANE BIOREACTOR TECHNOLOGY FOR PRE-TREATMENT

Report to the
Water Research Commission

by

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WRC Report No. 1894/1/14
ISBN 978-1-4312-0564-6

July 2014

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This report emanates from the Water Research Commission project K5/1894, entitled: Wastewater Reclamation for Potable Reuse. Also available is *Volume 2: Integration of MBR technology with advanced treatment processes* (**WRC Report No. TT 611/14**).

EXECUTIVE SUMMARY

Background and Motivation

There are a range of technologies, and combinations of treatment technologies, that can be used to reclaim water from domestic wastewater effluent. The choice of treatment train that will meet quality, cost and operational requirements is thus a difficult one. The intention of this research project is to test a range of advanced treatment technologies in different combinations and to establish a preferred reclamation treatment process train for the Darvill Wastewater Works (WWW) in KwaZulu-Natal. The product water quality derived from the reclamation process should meet both South African and international drinking water standards. Reclamation is being considered by Umgeni Water, the regional water utility, as an option to meet growing water demands within its supply area. Although indirect potable reuse (IPR) projects are widespread, direct potable reuse (DPR) is still only practiced in two places in the world, both in southern Africa. It is envisaged that the results from this study will reaffirm and give renewed confidence to the idea that the highest quality drinking water can be produced regardless of the source water quality. Technology has developed to such an extent that reclaimed water facilities can provide water that is of a higher quality than conventional public drinking water produced from surface water sources.

Objective

The main objective of this research project was to evaluate the performance of different membrane bioreactors (MBRs) as pre-treatment step to produce potable water.

Methodology

Three MBR pilot plants were set up onsite at the Darvill WWW. Settled sewage was pumped to a 20 kl balancing tank from where submersible pumps supplied each pilot plant. The three MBR pilot plants utilised different membrane technologies, thus providing an opportunity to compare performance. The MBR pilot plants and the membrane technology used were from Toray (Flat Sheet), Norit (Tubular) and Pall Corporation (Hollow Fibre). Unfortunately the Pall Corporation pilot plant was never successfully commissioned and therefore only the Toray and Norit pilot plants were trialled. Daily samples were taken and analysed for a period of one year. The pilot plants were operated and monitored by graduate Process Engineering students from the Durban University of Technology and the operability of the plants was noted.

The utilisation of an MBR system as a pre-treatment step in the reclamation process was evaluated in terms of the operability and filtration performance. The filtration performance was evaluated in terms of:

- Composition of the permeate
- Fouling potential of the permeate
- Fouling rate (cleaning frequency)
- Stable fluxes
- Peak fluxes.

The most important criteria evaluated in the MBR system was the composition of permeate produced. Permeate water quality is important because a poor permeate water quality can have a negative impact on downstream advanced water treatment processes. For example, the fouling potential for downstream membrane process e.g. reverse osmosis (RO) is a critical factor to be considered. The water quality was evaluated in terms of the permeate water quality being able to consistently meet set water quality objectives and standards.

Summary of Results

The performance of the Toray and Norit MBR systems was evaluated. Based on the operating experience and recorded MBR performance, the predicted average flux for the submerged Toray MBR system was 17 lmh, whereas the predicted average flux for the external Norit MBR system was 37.5 lmh. The predicted peak flux for the Toray membrane was 20 lmh whereas for the Norit external membrane was 45 lmh. The predicted cleaning frequency was every 5-6 weeks for the Toray MBR and every 7-8 weeks for the Norit MBR. The sustainable flux rates calculated at Darvill for the Toray and Norit membranes were lower than predicted for domestic sewage by the manufacturers. Darvill WWW influent sewage has approximately a 10% industrial component and this appears to have impacted negatively on the sustainable flux rates. The calculated membrane cleaning cycles were also higher than predicted, indicating possible membrane fouling.

Chemical cleaning regimes were, however, very successful in restoring original flux rates. In terms of water quality, the Norit membrane performed better than the Toray membrane with respect to microbial rejection, achieving zero values in the permeate for both faecal coliforms and coliphages. This was somewhat expected as the pore size of Norit (0.03 µm) is less than that of Toray (0.08 µm). Removal of suspended solids was the same with permeate nephelmetric turbidity units (NTU) = 0.3 for both membranes.

The permeate water quality from both MBR systems met or was close to the stated target water quality objectives, which were established through a literature search and discussions with the MBR pilot plant suppliers. Notable exceptions were found with the permeate chemical oxygen demand (COD = 20 mg/l) in both plants and the nitrate (NO_3 = 6.5 mg/l) values in the Toray pilot plant permeate. The target COD value of less than 10 mg/l may, however, have been reached, but could not be assessed because of a COD detection limit of 20 mg/l at the local Umgeni Water laboratory. The denitrification process in the Toray bioreactor was negatively impacted upon by over oxygenation. 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 return activated sludge (RAS) stream was rich in DO. As the RAS stream is returned directly to the anoxic zone, this flow may deplete the influent readily biodegradable COD needed for denitrification. The MBR pilot plants' performance in terms of biological nutrient removal (COD, NH_3) and microbial rejection (SS, coliforms) was comparable to other demonstration plants referenced in the literature review. The study showed that MBR technologies, both submerged and external (sidestream), produce excellent permeate water quality. The MBR technology could thus be recommended for use as a pre-treatment step for advanced wastewater treatment technologies. The Toray MBR demonstration plant was retained for use in Phase 2 of the reclamation plant study having proved to be the most reliable and easy to operate of the pilot plants.

Conclusions and Recommendations

The principal health concerns of DPR schemes are acute microbial risks, but these are managed effectively because of the application of proven water treatment technologies and the multiple-barrier approach. All the process trains proposed and tested recorded zero values for *E.coli* and coliphages in the final product water, throughout the trials. The level of trace organics was also consistently reduced by greater than 96% for the range of contaminants tested. MBR proved to be an ideal pre-treatment technology for the downstream advanced treatment processes. As the use of MBR becomes more common in South Africa, the opportunities for reclamation should increase. Defining treatment objectives for the MBR permeate narrows the concentration range of contaminants that can adversely impact the advanced treatment technologies. This should improve the performance and longevity of these advanced technologies by ensuring that the feed water is of appropriate quality e.g. SDI < 3 for reverse osmosis. A reduction in relative costs would be achieved through diminishing operating pressure and cleaning in place frequency events, thus diminishing membrane replacement requirements and associated investment.

ACKNOWLEDGEMENTS

This project was funded by the Water Research Commission (WRC) and Umgeni Water.

The project team wishes to thank the following people for their contributions to the project. First, the guidance and input of the WRC Reference Group is acknowledged with special reference to Dr Jo Burgess.

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In addition, the support and contributions of the following people is gratefully acknowledged:

Mr S Gillham	GM Engineering & Scientific Services
Prof L Pillay	Durban University of Technology (DUT)
Mr C Murutu	DUT
Mr P Thompson	Umgeni Water
Mr R Rajagopaul	Umgeni Water
Mr N Toolsee	Umgeni Water
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Special thanks also go to Mr N Gumede, Mr S Chiburi, Mr L Mkhwanazi, Mr S Chiburi and Ms N Mbambo for operating the plants, taking samples and generally doing more than asked to keep the plants running.

Umgeni Water Process Services, under the leadership of Mr P Thompson, provided all the necessary support and process expertise. Messers Rajagopaul and Toolsee are gratefully acknowledged for their design of the ozonation and GAC plants and Mrs Trollip for all her assistance.

All the Umgeni Water Laboratory Services management and staff members who were involved in the analysis of the samples for the project are thanked for accommodating the extra work load so graciously.

Darvill Wastewater Works operations staff is thanked for their patience and invaluable assistance in solving problems and always being willing to help.

This project would not have been possible without the contributions of various technology suppliers who went out of their way to provide assistance wherever possible. Special reference must go the MBR suppliers CHEMIMPO (Toray) and Pentair (Norit) represented by Mr J Naidoo and Mr T Moodley respectively. Mr P Groszmann (Toray) and Mr E Scharenborg (Norit) are also thanked for their invaluable and on-going assistance throughout the project. A number of membrane suppliers are thanked for providing a wide variety of membranes and these included DOW, Inge, Hydranautics and Toray.

Finally, last but not least, to my co-authors and especially Prof L Pillay and Mr C Murutu for their tireless enthusiasm and hard work and whose commitment to the project never waned.

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ACRONYMS, ABBREVIATIONS AND SYMBOLS

AOP	Advanced Oxidation Process
AS	Activated Sludge
AST	Activated Sludge Tank
BAC	Biological Activated Carbon
BOD	Biochemical Oxygen Demand
CAS	Conventional Activated Sludge
CEC	Contaminants of Emerging Concern
CFU	Colony Forming Unit
CIP	Cleaning in Place
COD	Chemical Oxygen Demand
DSVI	Diluted Sludge Volume Index
DAF	Dissolved Air Flotation
DBP	Disinfection By-products
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DPR	Direct Potable Reuse
DUT	Durban University of Technology
EBCT	Empty Bed Contact Time
EDC	Endocrine Disrupting Compound
ELISA	Enzyme Linked Immunosorbent Assay
F:M Ratio	Food to Mass Ratio
FS	Flat Sheet
GAC	Granular Activated Carbon
H_2O_2	Hydrogen Peroxide
HF	Hollow Fibre
HAZOP	Hazard and Operability Study
HRT	Hydraulic Retention Time
I/O	Input/Output
IPR	Indirect Potable Reuse
LC-OCD	Liquid Chromatography-Organic Carbon Detection
Lmh	Litres per square metre per hour
LRV	Log Removal Value
MBR	Membrane Bioreactor
MF	Microfiltration
mg/l	Milligrams Per Litre
MLE	Modified Ludzack-Ettinger
MLSS	Mixed Liquor Suspended Solids
MPN	Most Probable Number
MWCO	Molecular Weight Cut-off
NaOCl	Sodium Hypochlorite
NDMA	Nitrosodimethylamine
NF	Nanofiltration
NGWRP	New Goreangab Wastewater Reclamation Plant
NH_3	Ammonia
NO_3	Nitrate
NTU	Nephelometric Turbidity Units

O&M	Operation and Maintenance
O_3	Ozone
OCWD	Orange County Water District
P	Phosphate
PFU	Plaque Forming Units
PLC	Programmable Logic Control
PPCPs	Pharmaceuticals and Personal Care Products
PUB	Public Utilities Board (Singapore)
PVDF	Polyvinylidene Fluoride
RAS	Return Activated Sludge
RO	Reverse Osmosis
SAD_m	Specific Aeration Demand Based on Membrane Area
SAD_p	Specific Aeration Demand Based on Permeate Volume
SCADA	Supervisory Control and Data Acquisition
SDI	Slit Density Index
SRP	Soluble Reactive Phosphorous
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
UV	Ultra-violet
UWC	University of the Western Cape
WRC	Water Research Commission
WWW	Wastewater Works

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

South Africa is the 30th most water scarce region in the world, with unevenly distributed rainfall and runoff. The country has been classified as "water stressed" and water should therefore be conserved. The demands on surface and groundwater supplies should be reduced, or kept at current levels, rather than increased, as the country's population and industrial development increase. Wastewater reuse offers an opportunity to reduce demand on existing resources, and reclaiming domestic wastewater from Darvill Wastewater Works (WWW) for potable reuse is therefore proposed. The Umgeni System in which Darvill WWW is situated requires urgent augmentation and therefore any additional means of water supply will be beneficial. Globally, there are many types of water reuse schemes operating successfully. These range from agricultural and urban irrigation schemes to industrial and potable reuse schemes. There are, however, only two direct potable reuse (DPR) schemes at present, in Windhoek, Namibia, and Beaufort West, South Africa. Other potable reuse schemes are commonly indirect potable reuse (IPR) schemes, which use some form of natural buffer such as a dam, before re-treating and utilising the water for drinking.

A wide variety of treatment technologies are used to treat wastewater to potable standards. Treatment technologies are often combined to create a "multiple barrier" effect in contaminant removal. Multiple barriers are preferred because of the added safety benefit and risk reduction, especially if the end goal is potable reuse. No particular combination of treatment technologies has yet been established as the benchmark for potable wastewater reuse. This is understandable as each reuse scheme has a particular influent water quality and final water quality objectives. Treatment trains are thus designed to particular influent conditions and quality objectives or may be adapted to new developments and technologies with time. One such example would be the addition of ultrafiltration (UF) as a final treatment step at the New Goreangab Wastewater Reclamation Plant (NGWRP) in Windhoek.

The intention of this research project is to test a range of treatment technologies in different combinations and to establish a preferred reclamation treatment process train for Darvill WWW. The product water quality derived from the reclamation process should meet both South African and international drinking water standards. Advanced water treatment is required for potable water reuse as secondary and tertiary treatment will not produce a water of sufficient quality to comply with drinking water standards. The current advanced treatment scheme has evolved over time, and now commonly includes microfiltration (MF), reverse osmosis (RO), and advanced oxidation (Leverenz et al., 2011). Conventional secondary and tertiary wastewater treatment technologies do not always provide an effluent of sufficient quality for downstream advanced treatment technologies. This is particularly true if membranes are to be used, as the risk of membrane fouling increases with deteriorating influent quality. The growing use of membrane bioreactors (MBR) in secondary wastewater treatment has resulted in high quality effluent streams and the opportunity for more reuse projects to be implemented.

MBRs represent an ideal pre-treatment technology for advanced downstream wastewater reclamation treatment technologies. MBR technology becomes economically attractive when high effluent quality is required for water reuse or as pre-treatment for ultrafiltration or reverse osmosis processes. As such, MBR was chosen as the first barrier in the reclamation process treatment train. Since MBR performance is highly dependent on feed water quality, true comparison of the performance of different MBR technologies can only be achieved when they are tested against the same feed water matrix (Judd, 2011). Therefore, this study undertook the simultaneous trialling of three MBR technologies challenged with the same feed water. The analysis and testing of the performance of these MBR technologies at a pilot scale is described in this report.

1.2 PROJECT AIMS AND OBJECTIVES

1.2.1 Aim

The main aim of this project was to pave the way for technology that will enable South African water suppliers to produce consistent, acceptable drinking water quality through used water reclamation. In this study, the performance of MBR technologies as a pre-treatment step for advanced water treatment processes to produce potable water was evaluated.

1.2.2 Objective

As set out in the Water Research Commission Research Proposal No K5/1894 the main objective of this project is as follows:

"Analyse and test chosen process technologies e.g. filtration performance for different influent qualities and operational conditions against manufacturing specifications and report on the results"

1.3 APPROACH

The use of an MBR system as a pre-treatment step in the reclamation process was evaluated in terms of the filtration and operability performance. The filtration performance was evaluated in terms of:

- Fouling potential of the permeate
- Fouling rate (cleaning frequency)
- Stable fluxes
- Peak fluxes.
- Composition of the permeate – the performance of the MBR system was evaluated in terms of the composition of permeate produced. Permeate water quality is important because of the negative impact poor water quality can have on downstream advanced water treatment processes. For example the fouling potential for a downstream membrane process such as reverse osmosis (RO) is a critical factor to be considered. The water quality was evaluated in terms of whether the effluent water quality consistently met set water quality objectives and standards.

The operability of the MBR systems was evaluated in terms of the following criteria:

- Ease of operation and skill level required
- Control complexity
- Cleaning frequency
- Modes of operation
- Sensitivity to feed variations
- Recovery from upsets (failure of pre-treatment, power outages, air stoppage, pollutants in feed)
- Stability, reliability (equipment durability) and robustness of the system.

1.4 SCOPE AND LIMITATIONS

Operating cost is also an important criterion in technology selection, and a literature search was used to gain information on this topic. Because of scale i.e. equipment and process issues, actual demonstration plant running costs were not considered transferable for use in full-scale plant design and were therefore not analysed.

CHAPTER 2: LITERATURE REVIEW

2.1 WATER REUSE MARKET REVIEW

Global water reuse capacity will rise from 19 million m^3/day in 2005, to 55 million m^3/day in 2015 – a 181% increase over the decade. The market for water reuse is driven by rising demand for water, and the scarcity of new supplies. The water reuse market is expected to grow at an even faster rate than desalination and this is attributable to the following factors (Global Water Intelligence, 2005):

- There is strong political support for water reuse. Whereas growing environmental concern about discharges restricts the desalination market, the same concerns drive forward the market for water reuse.
- Investment in wastewater infrastructure will increase the availability of wastewater for reuse.
- The maturity of membrane technologies (including membrane bioreactors) in the wastewater treatment sector has reduced costs and broadened the scope of the wastewater reuse market.

The market for water reuse can be divided according to the type of treatment required (primary, secondary, tertiary or advanced water treatment), according to the source of the wastewater and according to the end user. The degree of treatment required in the reclamation process is an important issue in defining the market for water reuse, as high levels of treatment require greater levels of expenditure, and involve different equipment markets. Most countries require a degree of tertiary treatment before reclaimed water can be used without restriction in agriculture and municipal applications. Typically this involves a coagulation/flocculation, sedimentation, filtration and disinfection train. The United States Environmental Protection Agency (USEPA) suggests the following applications for tertiary treated wastewater:

- Food crop irrigation
- Landscape and golf course watering
- Vehicle cleaning
- Unrestricted recreational impoundment
- Toilet flushing
- Industrial process water
- Indirect potable reuse: groundwater recharge and surface water augmentation.

2.1.1 Market Drivers

There are five main macro drivers of water reuse:

- Increased demand for water
- Reduced availability of water supply
- Affordability
- Practicality of water reuse as a local solution
- Public policy.

Additionally water reuse has a number of attractions at a practical level for water utilities and businesses considering alternatives to their existing water resources. On the negative side water reuse also has drawbacks. These advantages and disadvantages are summarized in Table 2.1 (Global Water Intelligence, 2005).

Table 2.1: Advantages and Disadvantages of Water Reuse

Advantages	Disadvantages
It is a sustainable and reliable resource regardless of weather patterns.	In most parts of the world it has yet to be accepted for direct potable use.
It is available where the population is and can grow in direct proportion to the wastewater growth.	A separate distribution infrastructure is often required for reuse water.
It may be cheaper than other alternatives e.g. a new dam.	There is often a mismatch between where wastewater is (in cities) and where reused water is needed (in agriculture).
If not used for potable water it at least frees up other raw water sources for potable uses.	There are low levels of wastewater collection in many areas suffering from water scarcity e.g. North Africa.
It is a local solution to water scarcity where political issues complicate diverting resources from elsewhere.	
It turns an environmental hazard into an environmental asset e.g. water for parks, leisure facilities.	
It may be a cost effective alternative to building separate water & wastewater treatment plants.	
The water reuse industry has demonstrated rapid returns on investment	

Local scarcity rather than national scarcity is a more important factor in determining the growth of the market for water reuse. At present, the Middle Eastern nations of Israel, Jordon, and Syria reuse more than 70 per cent of wastewater. Abu Dhabi plans to reuse 100 per cent by 2015. In Singapore, which reuses 30 per cent of its wastewater, the reclaimed water, which is called NEWater, is used for drinking water indirectly and Beijing, China, set a goal of 100 per cent reuse by 2013 (Desalination and Water Reuse, 2011).

2.1.2 Water Reuse Technologies

The following processes are commonly used in reuse applications following secondary treatment processes:

- Filters (granular, single, multimedia and automatic backwashing filters)
- Adsorption (granular activated carbon)
- Ion exchange

- Membrane processes (microfiltration, ultrafiltration and reverse osmosis)
- Evaporation
- Membrane bioreactors.

Among the several techniques available for water reclamation, the membrane bioreactor (MBR) is a proven technology that combines biological treatment with a membrane separation process, thereby providing effluent low in particulate and organic matter. The advantages offered by an MBR compared to a conventional activated sludge process are reduced footprint, consistent and superior water quality, potential low sludge production, and solids separation independent of mixed liquor suspended solids (MLSS) characteristics. As the secondary clarifiers are eliminated in the MBR process along with a reduced volume of aeration tank due to higher operating MLSS concentration, MBR offers a significantly reduced footprint compared to the conventional activated sludge process (DeCarolis et al., 2009). The effluent produced from an MBR has to pass through a microfiltration (MF) or ultrafiltration (UF) membrane; hence, the water quality is superior and free of certain chorine resistant pathogens such as *Cryptosporidium* and *Giardia*. This very compact arrangement produces a MF/UF quality effluent suitable for reuse applications or as a high quality feed water source for RO treatment (Chapman et al., 2006).

2.2 MBR FUNDAMENTALS

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 2.1, 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).

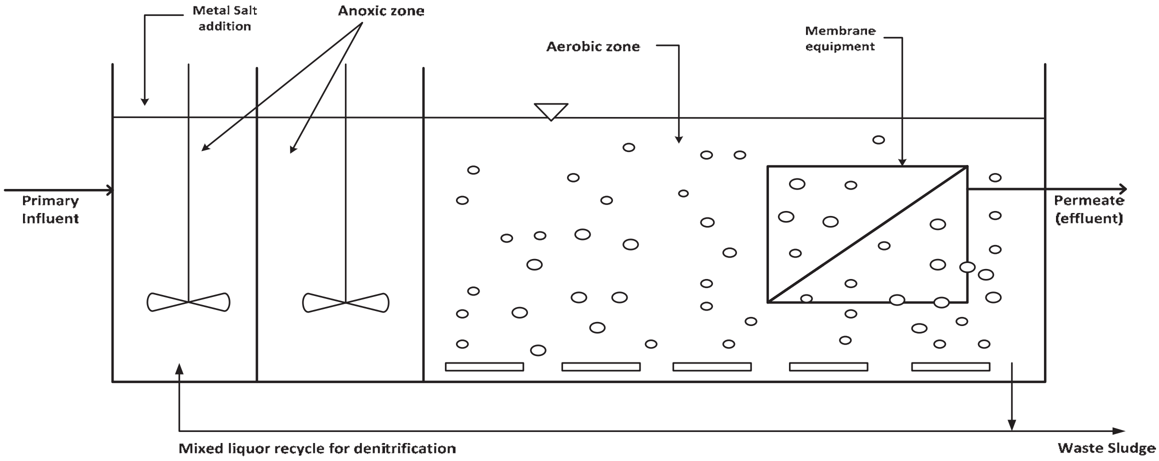


Figure 2.1: Membrane Bioreactor System Arrangement

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, which has a number of advantages especially with regards to general maintenance and removal of membrane modules. 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.

2.2.1 Pre-treatment

More rigorous screening is required for MBRs than for activated sludge (AS) plants as they are sensitive to debris in the sludge clogging the membranes and aeration system. Typically, flat sheet membranes e.g. Toray, use 3 mm screens, whereas hollow fibre systems e.g. Pall Corporation, require at least 1 mm. If the screen is not sufficient, fails, or is bypassed and debris gets 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).

2.2.2 Filtration

The ability of the MBR to filter is only limited by the 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 fouling and 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).

2.2.2.1 Trans Membrane Pressure

The trans membrane pressure for the MBR pilot systems was calculated as follows:

For submerged MBR systems (i.e. Pall and Toray)

TMP (mBar) = Static Pressure – Dynamic Pressure *(1)*

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

For external MBR system (i.e. Norit)

TMP (Bar) = ((Module Top Pressure + Module Bottom Pressure)/2) *(2)*

2.2.2.2 Flux

The flux of the MBR membranes was 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^3h^{-1})

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

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

Where:

J_{sp} = (lmh/bar)

J = Flux (lmh)

TMP = Tans membrane pressure (bar)

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

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

Where:

J_{net} = Net Flux (lmh)

J = Membrane Flux (lmh)

J_{BW} = Backwash flux (lmh) (backwash flux/membrane area)

T_F = Filtration time (min)

T_{BW} = Backwash time (min)

2.2.3 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^3h^{-1}). The HRT of the MBR system was calculated as follows:

$$HRT = \frac{V}{Q} \tag{7}$$

Where:

V = Volume of the bioreactor (m^3)

Q = Influent flow rate (m^3h^{-1})

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, though, only the sludge solids in the aeration tank and the waste sludge stream are considered. During operation, 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^3h^{-1}) by:

$$SRT = V \times \frac{MLSS}{Q_w} \times MLSS = \frac{V}{Q_w} \tag{8}$$

Where:

V = Volume of the bioreactor (m^3)
Q_w = Wasting flow rate from bioreactor (m^3/h)

As the membrane in an MBR rejects all solids, the sludge age can, in theory, be increased continuously. The higher the SRT, the higher will be the MLSS concentration. MBR systems are generally designed at high 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, European 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).

2.2.4 Food to Microorganism 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. The F:M ratio is given by:

$$F:M = \frac{COD \times Q}{MLSS \times V} \qquad (9)$$

Where:
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).

2.2.5 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 flatsheet (FS) and hollowfibre (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.

2.2.6 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, which 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 that 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, which 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, which dissolves the organic matter and/or hypochlorite, which 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 which were not in contact with the chemical during the first clean. Chemical cleaning cannot remove all fouling on the membrane surface and this is termed irrecoverable fouling. Cleaned membranes have lower fluxes than new membranes and therefore irrecoverable fouling dictates the membrane life.

2.2.7 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). Fullscale 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 2.2 (Wastewater Engineering, 2004 p. 1128).

Table 2.2: 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

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

$$\text{Log removal} = \text{Log}(c_f) - \text{Log}(c_p) \quad (10)$$

Where:

c_f = Concentration in the MBR influent

c_p = Concentration in the MBR permeate.

2.2.8 MBR Configurations

MBR systems are available in two different configurations: "sidestream" or "submerged", as shown in Figure 2.2 (Adham, 1998). In the sidestream configuration (Figure 2.2A), 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 industrial applications due to the high energy cost required to maintain proper cross flow velocities for sidestream membrane modules (Morgan et al., 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 buildup, and are chemically cleaned when operating pressures become too high.

In the submerged configuration (Figure 2.2B), 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).

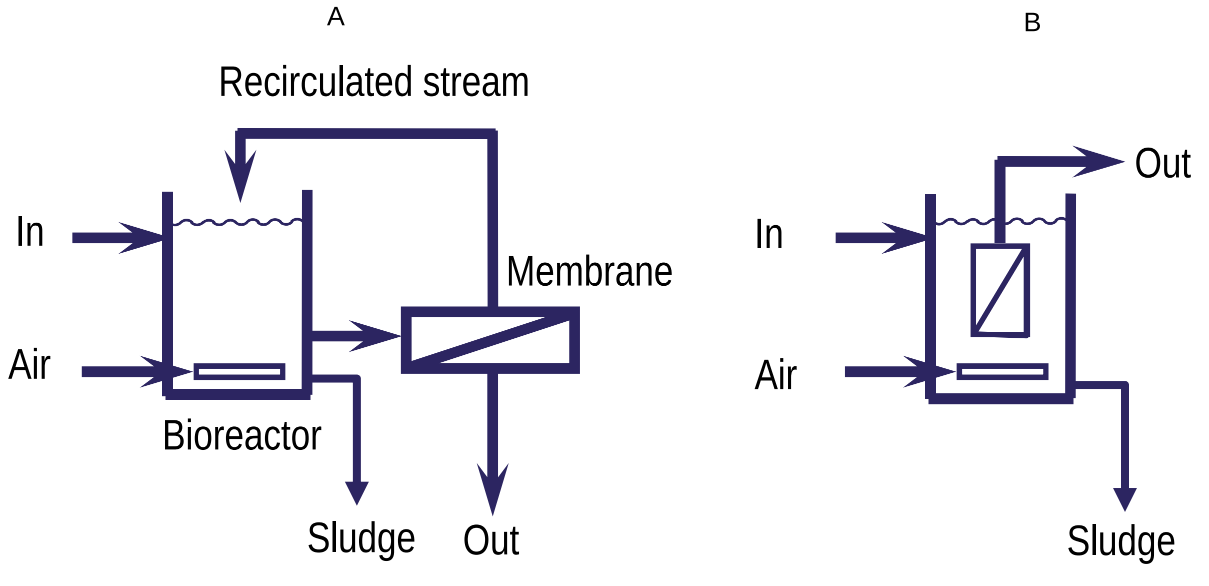


Figure 2.2: Configurations of a Membrane Bioreactor: (A) Sidestream, (B) Submerged

The different MBR configurations entail different risks for the operation of the plant. Submerged membranes can be either 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 relates 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 efficiency is twice 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 2.3), almost all submerged MBR membranes are either rectangular flat sheet (the original being the Kubota product) or vertically-oriented hollow fibres (the original being commercialised by Zenon).

Table 2.3: 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

2.2.9 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). 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, which include:
  - instantaneous flux
  - length of the period between backflushing and/or relaxation (air scouring without permeation)
  - duration of backflushing and/or relaxation
  - backflush flux or pressure
  - nature of chemical clean (frequency of chemically enhanced backwash and/or maintenance clean, composition and strength of chemical reagent)
  - 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 possible enabling optimum control of the microbial population and flexibility in operation. The membrane not only retains all biomass but prevents the escape 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, which 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).

2.2.10 Disadvantages of MBRs

The disadvantages associated with MBR 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 MBR retains all suspended solids and most soluble 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).

2.3 MBR CASE STUDIES

A number of studies have been undertaken around the world comparing the performance of different MBR systems at pilot scale and full scale. The results from these studies, more particularly those from the pilot scale studies, were used as a basis for comparing MBR performance and operating experiences with the Darvill study.

2.3.1 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 litres per square metre per hour (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 2.4. 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 complete 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 2.4: MBR Performance Comparison (Removal Efficiency %)

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					
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 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).Ultrafiltration membranes can achieve 4 to 6 log removal value (LRV) of MS2 bacteriophage, while microfiltration membranes are limited to 1 to 1.5 LRV (DeCarolis and Adham, 2007). The ability of ultrafiltration to outperform microfiltration, with respect to virus removal, is the result of the difference in membrane pore size (typically 0.01 versus 0.1 micron, respectively). Because a virus is approximately 0.025 micron in size, exclusion by microfiltration is only achievable by filtration through a dynamic cake layer formed on the membrane surface. The Zenon MBR achieved between 4.0 and 5.5 LRV removal of coliphage, with all permeate values at or below the detection limit of 1.0 PFU/ml. The projected cleaning cycle time, calculated from the permeability decline value and trans membrane pressure (TMP) boundary values of 0.1 and 0.5 bar, was similar for the three HF membranes. The cleaning cycle time of the Kubota membrane could not be established as there was no noticeable permeability decline. It appears that the inclusion of a denitrification step in the Kubota treatment train may have ameliorated fouling in some way (Judd, 2011). Effluent from the Kubota MBR was fed downstream to a RO membrane (Hydranautics LFC3), which operated with minimal fouling. The average net operating pressure of the Hydranautics LFC3 (fouling resistant) RO membranes measured during testing was 8.3 bar. A 1-2 mg/l dose of chloramine in the RO feed was effective in mitigating membrane fouling.

2.3.2 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 nephelometric turbidity units (NTU) and effluent 5-day biochemical oxygen demand (BOD_5) concentration of less than 2 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 milligrams per litre as nitrogen (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 2.5.

Table 2.5: Pilot Plant Permeate Water Quality Data

	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
NH3-N (mg/l)	0.3	0.2	0.2	0.2
NO_3 (mg/l)	29.3	15.2	9.8	4.2
NO2 (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	<8 (5-log)	<12 (5-log)	<10 (5-log)
Coliphage (CFU/100ml)	<10	<9 (3-log)	<11 (3-log)	<10 (3-log)
Virus (log removal 50^{th} percentile)	1-log	4-log	3-log	4-log

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

Additional steady state studies of flux sustainability at the recommended aeration rates were conducted. Results of steady-state operation indicated specific aeration demand of the membrane (SAD_m) values of 0.34-0.74 with accompanying SAD_p (permeate) values of 7.6-27, the lowest arising for the Norit sidestream airlift configured technology for which supplementary sludge pumping was employed The results of the studies are given in Ttable 2.6.

Table 2.6: Pilot Plant O&M Data (Judd, 2011)

Parameter	Puron	Huber	Toray	Norit
Membrane Aeration Rate, Nm^3h^{-1}	10.3	51.6	102.9	10.12
Cycle, min	6 on/0.33 backflush	9 on/1 relax	9 on/1 relax	10 on/1 backflush
Net Flux, lmh	22.6	25	27	45.7
HRT, h	4-11	8-15	5-7	7-11
Median SRT, d	13	15	20	33
MLSS, gl^{-1}	9-12	8-14	9-12	8-12
Cleaning Cycle Time, d	191	207	>920	332
Derived Data				
Max Permeability K, lmh/bar	340	250	390	420
SAD_m, Nm^3/m^2h^{-1}	0.34	0.48	0.74	0.35*
SAD_p, m^3 air/m^3 Permeate	15	19	27	7.6*

*Supplemented by sludge pumping at 11 x permeate flow rate.

During the course of the study, the RO system was operated for more than 1,500 hours on effluent from two different MBR systems. The RO unit consisted of two single pass trains and was operated at 50% recovery and 20 lm^2h^{-1} throughout the study period. The RO membranes operated on MBR effluent for a period of more than 1,300 hours without requiring a chemical clean. However, when a membrane breach occurred in one of the MBR systems, the RO membrane fouled overnight. As a result, the project team recommends that the membrane integrity of MBR systems be checked periodically to avoid any problems (U.S. Bureau of Reclamation, 2009).

2.3.3 Bedok Water Reclamation Plant, Singapore

Pilot trials were performed as part of research undertaken at the NEWater project. The NEWater process train consists of ultrafiltration/microfiltration as a pre-treatment step prior to RO. The MBR-RO option was explored by conducting trials of three MBR pilot plants operating simultaneously. The three MBR technologies are not specified in the report by Tao et al., 2005, 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 2.7. Pilot testing has shown the MBR-RO option to produce a slightly superior quality product water than the conventional approach of secondary treatment followed by UF/MF – RO specifically with respect to TOC, nitrate and ammonia (Qin et al., 2006), and also tends to be lower in cost.

Table 2.7: Pilot Plant Product Water Quality

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

The operational performance of the three MBRs is presented in Table 2.8. MBR B (Mitsubishi Rayon) is reported to have the lowest energy demand, but it should be noted that this MBR is the only one configured without a separate aeration tank.

Table 2.8: Pilot Plant O&M Data

Parameter	MBR A	MBR B	MBR C
Membrane	0.4 µm FS 0.8 m^2 panel area	0.4 µm HF 280 m^2 element area	0.035 µm HF 31.5 m^2 element area
Probable Technology	Kubota, double deck	MRE	Zenon (500d)
Membrane Area, m^2	480	1120	1008
Tank Volumes			
Anoxic, m^3	30.8	37.5	25.2
Aerobic m^3	11.4	–	27.9
Membrane, m^3	32.8	37.5	21.8
O&M			
MLSS gl^{-1}	6-12	6-14	4-13
Net Flux, lmh	13-28.4 (26)	16-24 (24)	6.2-29.3 (12.4)
Initial TMP, bar	0.04	0.17	0.1
Cycle, min	9 on/1 relax	13 on/2 relax	12 on/0.5 backflush+relax
Cleaning Cycle Time, d	90	120	3.5*
Chemical Cleaning Reagents	0.6% NaOCl, 1% oxalic acid	0.3% NaOCl, 2% citric acid	NaOCl, 1% oxalic acid*
Derived Data			
SAD_p, m^3 air/m^3	28-50 (50)	16-24 (24)	20-30 (30)
Init. Permeability K, lmh/bar	650	66	124
SAD_p, m^3 air/m^3 Permeate (Energy Demand, kWh/m^3)			
Baseline	50 (1.4)	24 (1.3)	30 (1.7)
High Flux	34 (1.2)	21 (1.0)	25 (1.3)
Low Aeration	28 (1.0)	16 (0.8)	20 (1.1)

*Maintenance clean employed; citric acid cleaning suspended after 11 months

2.3.4 Ulu Pandan

The success of the MBR trials at Bedok led the Singaporean Public Utilities Board (PUB) to construct a 23 Ml/d demonstration plant, which 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 bioreactors operate at a maximum MLSS of 10,000 mg/l, a minimum sludge age of 10 days, a HRT of 6 h and a minimum F:M ratio of 0.1 kg BOD/(kg MLVSS d). The membrane tank has five trains, each with five *ZW500c* cassettes, providing a total membrane area of 37,920 m^2. At the net design flux of 25 lmh the maximum MLSS in the membrane tank is 12,000 mg/l (Judd, 2011). The operators have optimised the aeration process so as to achieve an overall energy demand of 0.4 kWh/m^3. The influent and product water quality are presented in Table 2.9.

Table 2.9: Settled Sewage and Product Water Quality Data at Ulu Pandan

Parameter	Units	Average (Influent)	Range (Influent)	Permeate
BOD_5	mg/l	138	111-171	
COD	mg/l	292	236-420	
TOC	mg/l			4.8
TSS	mg/l	105	89-120	
Turbidity	NTU			0.02
TKN	mg/l	47.6	36.7-61.8	
NH_4-N	mg/l	32	20.5-46.6	
NO_3-N	mg/l			6.3
Coliforms	CFU/100 ml			<1
MLSS Temperature	^{0}C	30	28-32	
Total phosphate as P	mg/l	3.7	5.2-8.1	3.3
pH			6-8	

CHAPTER 3: MEMBRANE BIOREACTOR PILOT PLANT EVALUATIONS

3.1 DESCRIPTION OF THE STUDY SITE

The testing site is the Darvill Wastewater Works (WWW) in Pietermaritzburg, KwaZulu-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. The existing inlet works consists of two inlet channels each equipped with a hand racked coarse screen, a 12 mm front raked bar screen with screenings compactor and two vortex flow degritters. Primary treatment consists of three primary settling tanks. The biological process consists of an activated sludge reactor equipped with 15 no. surface aerators and 9 no. low speed mixers in the anoxic/anaerobic/aerobic zones. 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.

3.1.1 Location of the MBR Pilot Plants

The three pilot scale MBR units were located adjacent to the existing activated sludge tanks (ASTs) on an open piece of ground, and had direct access to the works' primary effluent. Influent to the demonstration MBR plants was abstracted at the inlet to the ASTs of Darvill WWW. A submerged pump discharges into the 20 kl feed storage tank from which the pilot plants draw directly. 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 3.1.

The Norit MBR pilot plant was installed and operated on a newly constructed concrete slab. The Toray and Pall MBR pilot plants are containerised and were 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 three MBR units 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 plant set-up is given in Figure 3.1 below and Figure 3.2 provides a picture of the set-up.

Table 3.1: Historical Darvill Wastewater Works Settled Sewage Water Quality (2000-2009)

	Units	**Mean**	**Std Dev**	**Median**	**95th %tile**	**Min**	**Max**	**No. of Analyses**
Al (T)	µg/l	1368	1034	1125	3358	76	3962	18
Alkalinity	mg $CaCO_3^{-1}$	**204**	58	202	275	10	822	475
Br	mg/l	0.10	0.00	0.10	0.10	0.10	0.10	15
Ca	mg/l	34	12	31	57	6.11	66	50
Cd	µg/l	1.00	0.00	1.00	1.00	1.00	1.00	17
$CHBr_3$	µg/l	0.10	0.00	0.10	0.10	0.10	0.10	16
$CHCl_2Br$	µg/l	0.18	0.17	0.10	0.55	0.10	0.62	16
$CHCl_3$	µg/l	1.10	0.55	0.80	2.12	0.80	2.35	16
$CHClBr_2$	µg/l	0.10	0.00	0.10	0.10	0.10	0.10	16
CN (Soluble)	µg/l	16.6	15	10	36	10	43	5
CN (Total)	µg/l	31.8	49	12	101	10	214	18
COD	mg/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
Fe (S)	mg/l	0.34	0.24	0.23	0.57	0.17	0.61	3
Fe	mg/l	1.85	2.86	0.58	10	0.15	10	208
Hardness (T)	mg $CaCo_3$/l	135	28	131	176	97	192	14
Hg	µg/l	0.99	0.8	0.60	2.1	0.5	3.3	18
K	mg/l	8.04	1.7	8.5	9.8	3.7	10	37
Mg	mg/l	7.0	3.9	6.3	8.9	4.30	33.00	51
Mn (S)	mg/l	0.09	0.03	0.09	0.12	0.06	0.12	3
Mn	mg/l	0.15	0.04	0.14	0.22	0.11	0.28	18
Na	mg/l	113	16	110	131	98	134	4
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
Si	mg/l	5.1	0.71	5.10	6.19	3.81	6.46	18
SO_4	mg SO_4/l	56	23	54	92	27	114	18
SRP	µg P/l	3985	2705	3580	8830	170	21420	473
SS	mg/l	**86**	39	80.00	154	4.00	332	475
THM	µg/l	1.00	0.63	0.80	2.30	0.80	2.75	16
TKN	mg N/l	**29**	9.81	28.80	45.16	5.49	62	285

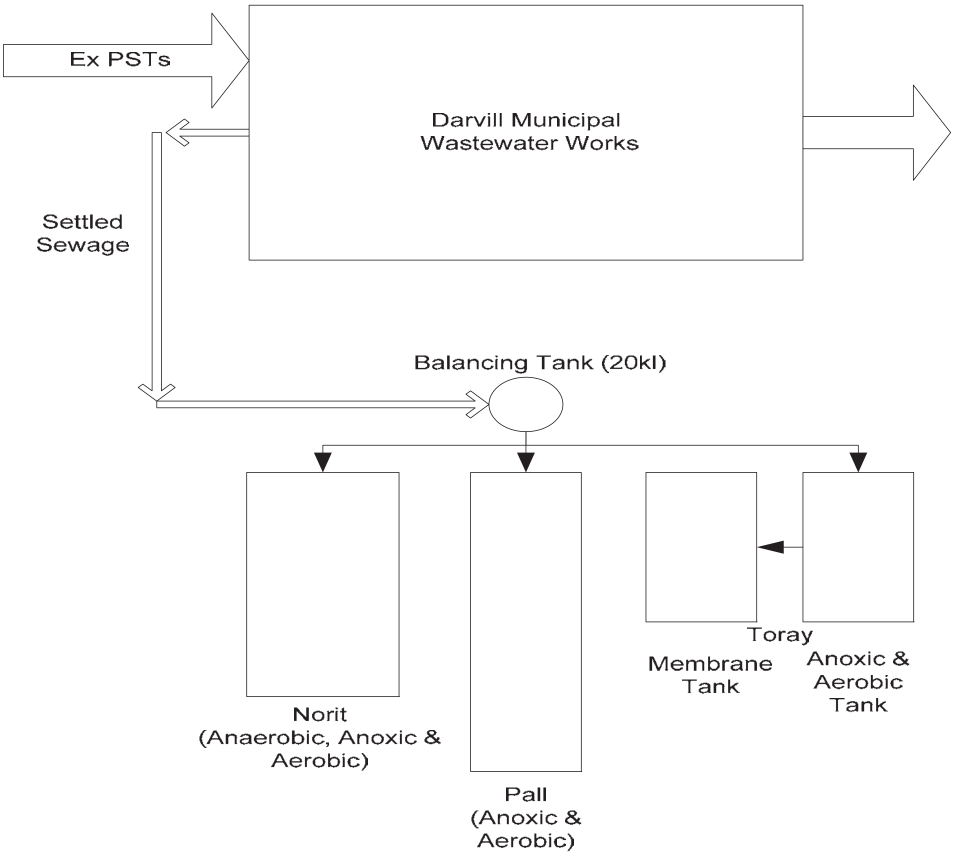


Figure 3.1: Plan Layout of MBR Pilot Plants

Figure 3.2: Onsite MBR Pilot Plant Set-up

3.2 DESCRIPTION OF MBR PILOT PLANTS

3.2.1 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 3.3. 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 **A**nnexure A-A**.**

Figure 3.3: Norit MBR Pilot Plant showing Drum Screen

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 3.4. 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 3.4: Norit MBR Pilot Plant Showing External Membrane Module

3.2.2 Toray MBR

The Toray MBR pilot plant provided by CHEMIPO (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 **A**nnexure A-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.

3.2.3 Pall Corporation MBR

The Pall MBR pilot plant provided by Pall Corporation is an automated system that combines aerobic biological treatment with a submerged membrane. The Pall MBR pilot plant consists of a 30 m^3 aerobic tank, 15 m^3 anoxic tank, and a submerged membrane module in a 10 m^3 membrane tank. Feed water to the system is screened by a 0.75 mm Roto-sieve drum screen before being passed to the anoxic basin. Feed flow to the anoxic basin is controlled via a PLC using a submersible pump. From the anoxic tank, water flows by gravity to the aeration tank for nitrification. Nitrified water from the aeration tank is recirculated back to the anoxic tank for denitrification. Water from the aeration tank is also recirculated to the membrane tank at a flow rate of four times the permeate flow. Sludge wasting is done automatically from the aeration tank and it is controlled via a PLC after receiving an output from a TSS sensor submerged in the aeration tank. The Pall membranes are immersed in the membrane tank of mixed liquor. A vacuum is applied to the top header of the membrane modules and water is drawn from outside in through the hollow fibres. The Pall MBR pilot system consists of a Pall Aria Microza PVDF HF membrane module with a nominal pore size of 0.1 µm and a membrane area of 30 m^2. These submerged HF membranes are bundled in a unique fashion which, when air is introduced at the bottom of the module, eliminates accumulation of sludge at the top of the module and lowers fouling rates. The system is purported to operate efficiently at MLSS concentrations up to 10,000 mg/l. The plant configuration is represented graphically by a process flow diagram in **A**nnexure A-A.

A HAZOP was completed prior to commissioning the demonstration plant in November 2010. Unfortunately a pipe burst a day after commissioning, flooded the inside of the plant operating container. The plant had to be shut down as all the mechanical equipment had to be removed to be cleaned and checked. The plant was to be re-commissioned in December 2010, but following contractual issues with the local contractor, Pall Corporation thought it best if they end their participation in the project. The Pall Corporation MBR demonstration plant was thus not used any further in this project and there are no results to report on the performance and operation of this plant.

3.2.4 Pilot Plant Specification Summary

A summary of the demonstration plant specifications is given in Table 3.2.

Table 3.2: Summary of MBR Pilot Plant Specifications

	Norit	**Toray**	**Pall**
Membrane Type	Tubular	Flat Sheet	Hollow Fibre
Configuration	External	Submerged	Submerged
Pore Size (µm)	0.03	0.08	0.1
Reactors	Anaerobic, Anoxic, Aerobic	Anoxic, Aerobic	Anoxic, Aerobic
Operational Period	June 2010 - July 2011	Nov 2010 -July 2011	None

3.3 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. Details of the CIP procedure and the recommended concentration of cleaning chemicals are given for both the Toray and Norit plants in annexure A-B.

3.4 ONSITE SAMPLE COLLECTION AND ANALYSIS

3.4.1 Sample Collection

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.

3.4.2 Methods of Analysis

3.4.2.1 pH

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

3.4.2.2 Turbidity

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

3.4.2.3 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.

3.4.2.4 Temperature (^oC)

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.

3.4.2.5 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.

3.4.2.6 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.

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

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

3.5 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 3.3.

Table 3.3: Umgeni Water Laboratory Detection Limits for Some Determinants.

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

3.5.1 Total Organic Carbon (TOC)

Umgeni Water Head Office laboratory measures total organic carbon (TOC) using a Tekmar Apollo 9001 TOC Analyser. The limit of quantification (LOQ) of this instrument is 0.5 mg/l and the limit of detection (LOD) is 0.2 mg/l, although the laboratory would not report lower than 0.7 mg/l. Although this is more than adequate for compliance with SANS:241-1:2011 drinking water standards (< 10 mg/l) it is insufficient for analysing TOC removal for wastewater reclamation purposes. The measurement of TOC is actually the measurement of Dissolved Organic Carbon (DOC) as the 5 µm filter used in the sample preparation removes all particulate TOC and only dissolved carbon remains. There are a number of reasons why a more accurate TOC (DOC) measurement is required, including:

- Advanced water treatment technologies such as nanofiltration (NF) and RO can remove TOC to below 1 mg/l. As both NF and RO can remove TOC < 0.7 mg/l, the LOQ precludes any comparison in removal efficiency.
- Similarly, comparison of results with other pilot studies or existing full-scale plants is meaningless as these facilities report on TOC results below the Umgeni Water LOQ.
- Permeate TOC is often taken as a surrogate for the removal of micro-organics and therefore the lower the LOQ the better the assumed result.

Although the LOD of the Tekmar Apollo 9001 TOC Analyser is technically < 0.2 mg/l, in reality the technicians operating the instrument were unable to achieve these limits. There were a number of reasons postulated for this, namely:

- The Darvill Laboratory, which also had a TOC instrument that was used, was a contaminated environment (especially atmospheric contamination) that made measurement of DOC very difficult. Reproducibility of results could not be achieved when calibrating the instrument. Strict sampling and instrument/calibration protocols are required, that are a lot easier to achieve in a controlled pharmaceutical laboratory than in a wastewater process facility.
- Blank readings on the milli-q water are very close to 0.1 mg/l due to dissolved CO_2. It was therefore very difficult to read to < 0.1 mg/l. To avoid absorption of CO_2 from the environment, very clean vials are

needed and they must be sealed. The longer the samples stand, the more CO_2 is absorbed, so sealing the vial with a septum is vital. The ambient carbon dioxide can dissolve in water during the preparation of solution(s) and that will contribute to the TOC results because at the normal pH the dissolved carbon dioxide will be converted into bicarbonate. This problem is negligible in the range the laboratory is working in, but at low concentrations will be significant. Samples and standards need to be prepared and kept in an inert environment before and during analysis.

- Accuracy will also be dependent on the purity of the standard. The way the standards are prepared, as with any analytical determination from a calibration curve, is difficult for TOC standards at low levels. For example, the pharmaceutical industry have complained in the past that to make standards lower than 100 ppb was difficult (organics in glassware, TOC level of reagent water, etc.). That is why they implemented the feature that the new Fusion can prepare standards online by diluting a stock standard solution with no other organic interference (Garside, 2012).

3.6 MBR WATER QUALITY OBJECTIVES

The targeted permeate water quality objectives for the MBR demonstration plants are provided in Table 3.4. The specifications aim to achieve the best possible effluent water quality from the MBR unit process. The specifications are proposed based on a literature review of water quality results obtained using MBR technology in various settings. These settings include example pilot scale plants and operational wastewater works. The manufacturers' specifications are also taken into account.

Table 3.4: Target Permeate Water Quality Objectives for MBR Demonstration Plants

Parameter	Target (mg/l)
BOD_5	2
COD	10
TSS	<1
TOC	7
Turbidity (NTU)	<1
Oil &Grease	<1.2
Ammonia (NH_3-N)	0.5
Nitrate (NO_3) as N	<6
Nitrite (NO_2) as N	<2
Total Nitrogen (TKN+NO_3+NO_2)	<10
Orthophosphate (SRP)	1
UV_{254} (abs/cm^{-1})	0.065
Total Coliforms (CFU/100ml)	<10
E.Coli (CFU/100ml)	0
Coliphage (PFU/100ml)	0

CHAPTER 4: RESULTS AND DISCUSSION

4.1 OPERATIONAL HISTORY AND PARAMETERS FOR THE MBR PILOT PLANTS

4.1.1 Toray MBR Operating History

The Toray system was initially commissioned in April 2010 when it was seeded with RAS from the nearby Darvill WWW aerobic basin. At that stage, the pilot plant had no biological treatment processes, so it was not representative of a fully-fledged MBR system. Umgeni Water requested that Toray add additional aerobic and anoxic tanks to the plant. 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. The bioreactor was commissioned in September 2010 and the full MBR system was operational in November 2010. A summarized timeline of the milestones is given below in Figure 4.1.

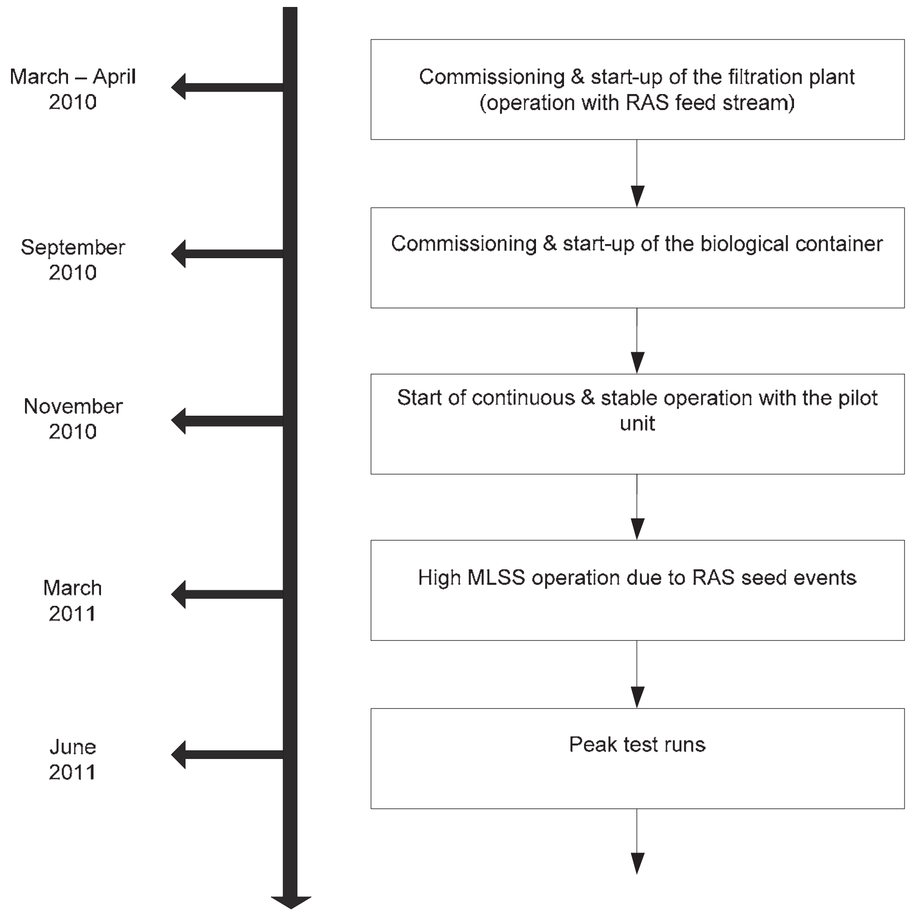


Figure 4.1: Milestones of Toray Pilot Plant History

The plant was operated throughout November 2010 but was offline for the majority of December 2010 because of an instrumentation failure. On the 1st of December 2010, 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, after which 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 inactivated all the sludge, reducing the MLSS concentration to less than 1,000 mg/l. The plant had to be completely drained and reseeded. Normal operation resumed on the 4th January 2011. The plant was operated without major incident for the next two months until the membrane tank aeration blower failed on the 15th March 2011. The blower had to be removed and repaired which meant that the plant was offline for a week. From March 2011 the plant operated consistently through to June 2011.

4.1.1.1 Toray MBR Operating Parameters

The Toray MBR plant was expected to achieve nitrification and denitrification. Significant removal of phosphorous was not expected because of the lack of an anaerobic zone. The system was seeded with sludge from the Darvill WWW ASTs in September 2010. The concentration of sludge from the Darvill ASTs is in the 4,000-5,000 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 is unclear but the plant was affected by a number of operational problems that resulted in plant downtime. These problems included mechanical and instrument malfunctions 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 low 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 suggests that the influent is not readily biodegradable, as a rule of thumb. Figure 4.2 presents the MLSS concentrations in the aerobic tank of the Toray MBR system. It is evident that prior to mid April 2011 the MLSS concentration was generally below 5,000 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 April 2011 a decision was made to seed the Toray MBR system with RAS which had a MLSS concentration in the 7,000-8,000 mg/l range. The MLSS has since remained above 10,000 mg/l and with occasional reseeding with RAS has been maintained at the target concentration of 10,000-15,000 mg/l.

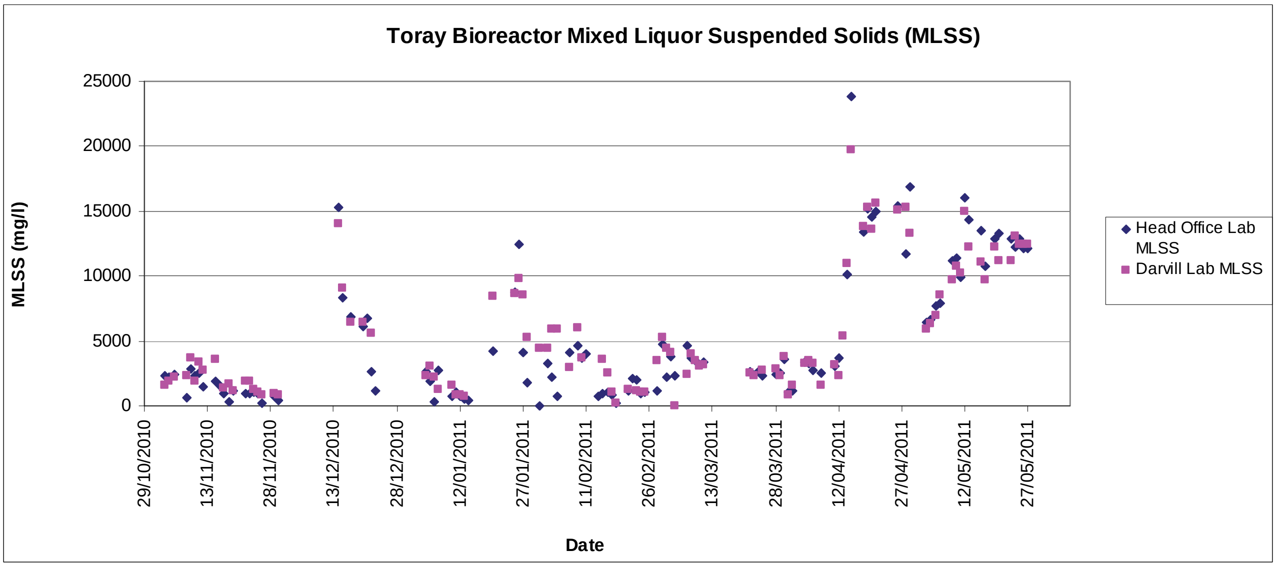


Figure 4.2: Toray Bioreactor MLSS Concentration (Nov 2011 - June 2011)

The targeted range for DO levels in the aerobic tank was 1-2mg/l. Figure 4.3 shows the actual DO concentrations for the Toray aerobic tank. As can be seen in the graph, the DO concentrations varied significantly from near zero to as high as 8 mg/l. Despite many attempts to regulate the variable speed drive 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 TMP operating range for the Toray plant is from -30 to -130 mbar and the maximum TMP is -180 mbar at which point an alarm will stop the plant.

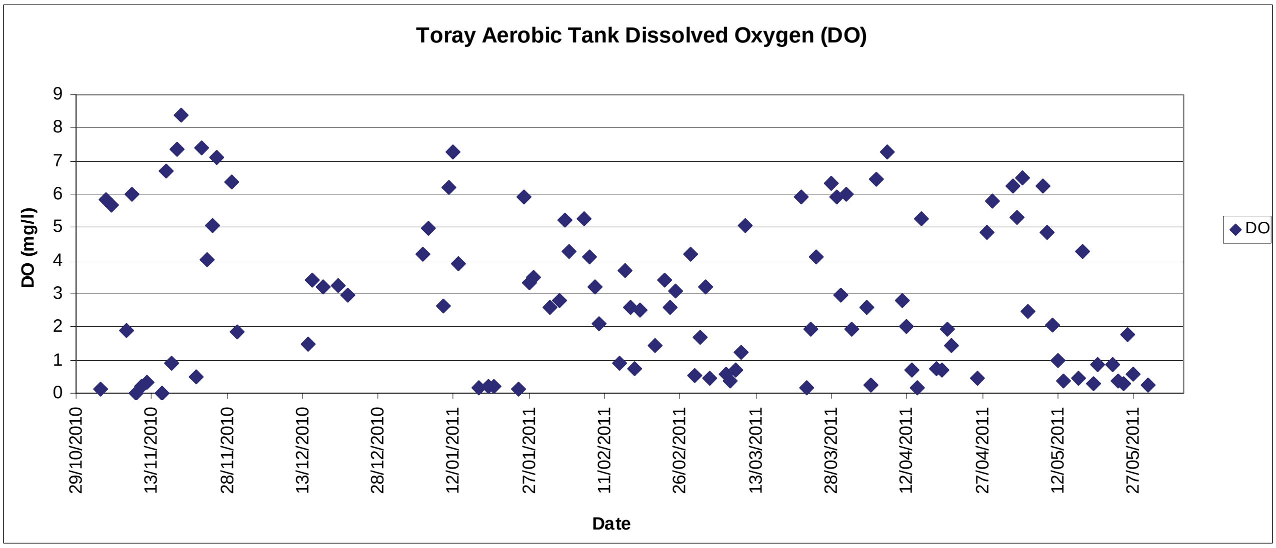


Figure 4.3: Toray Aerobic Tank DO Concentration (Nov 2010 - June 2011)

4.1.2 Norit MBR Operating History

The system was initially seeded with AS from the nearby Darvill WWW aerobic basin and was commissioned in May 2010. The first month's operation was problematic with a number of stoppages. This was partly due to the operators needing to learn how to operate the plant, but also as a result of random incidents such as power failures. The situation did not improve during June 2010, with a host of breakdowns and operational problems resulting in the plant being offline for most of the month. The pilot was then operated for four consecutive months, from July to October 2010, but not without problems, which caused many interruptions to operation. 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 Norit engineers, which was time consuming. The pilot plant operators and the Norit engineers were not available at night so any plant shutdown could not be attended to timeously. Overnight shutdowns resulted in time-consuming delays in getting the plant up and running again. On the 13th November 2010 the plant was shut down completely as there was a PLC failure that required new components to be imported from Holland. Once the components had arrived and had been installed, an attempt was made to restart the plant in mid-December 2010, but it was not successful. On the 18th January 2011, the plant was restarted and despite on-going minor problems was operational until the peak tests were run in June 2011.

4.1.2.1 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 ASTs in May 2010. The concentration of sludge from the Darvill ASTs is in the 4,000-5,000 mg/l range, but the MLSS concentrations remained below 4,000 mg/l in the bioreactor during the start-up period. The concentration of 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 demonstration plant from May 2010 to June 2011 in Figure 4.4. 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 the higher MLSS concentrations could not be maintained.

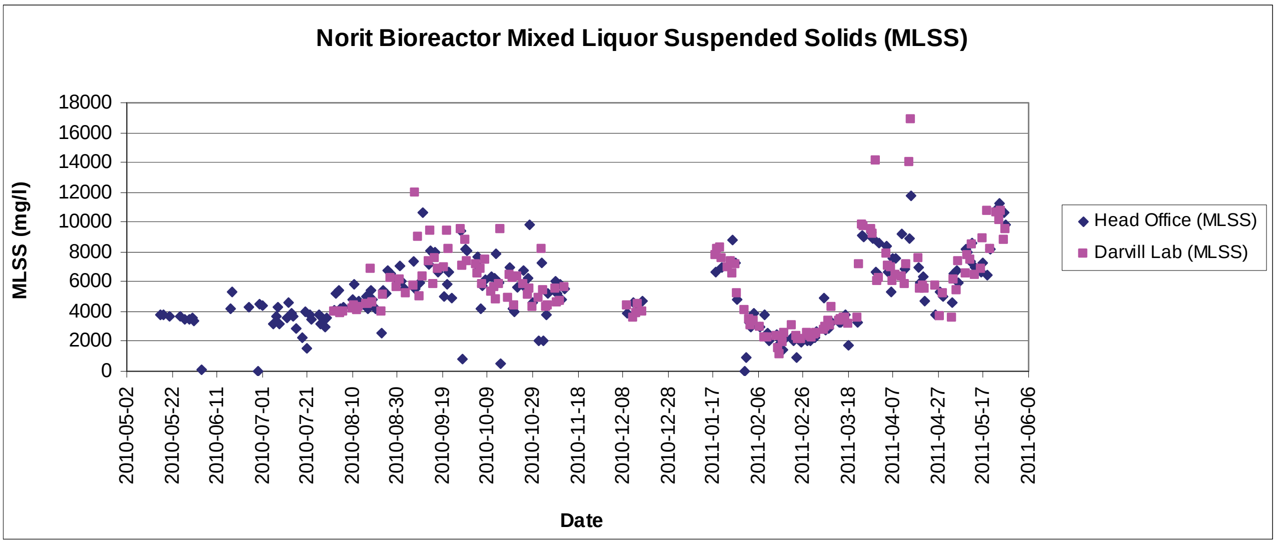


Figure 4.4: Norit Bioreactor MLSS Concentration (May 2010 - June 2011)

The targeted range for DO levels in the aerobic tank was 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 4.5. DO control was however more successful than with the Toray system as the average DO concentration achieved was 2.1 mg/l. The TMP operating range for the Norit plant is between 0.1 and 0.4 bar and the maximum TMP is 0.5 bar at which point an alarm will stop the plant.

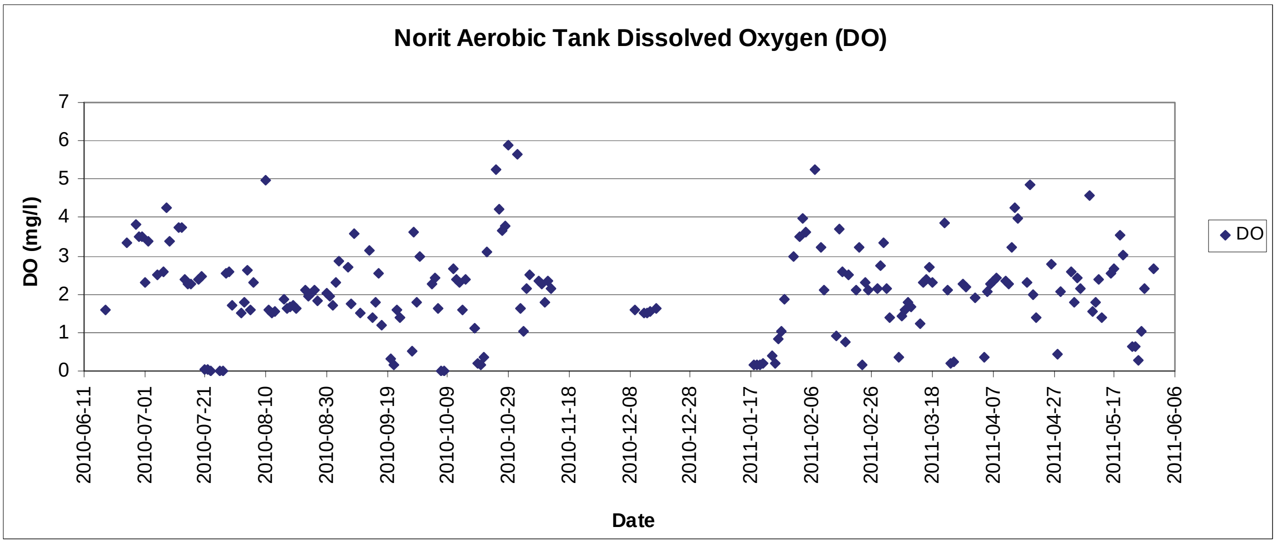


Figure 4.5: Norit Aerobic Tank DO Concentration (Nov 2010 - June 2011)

4.2 MEMBRANE PERFORMANCE RECORD AND EVALUATION

4.2.1 Toray Membrane Bioreactor System

4.2.1.1 Toray Membrane Performance Record

After the Toray MBR was seeded with sludge from the Darvill ASTs, the plant was operated at low fluxes (7 lmh) initially, 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 concentration 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 4.6 as well as the times when a cleaning in place (CIP) was undertaken. The flux and permeability data are presented in Figure 4.7.

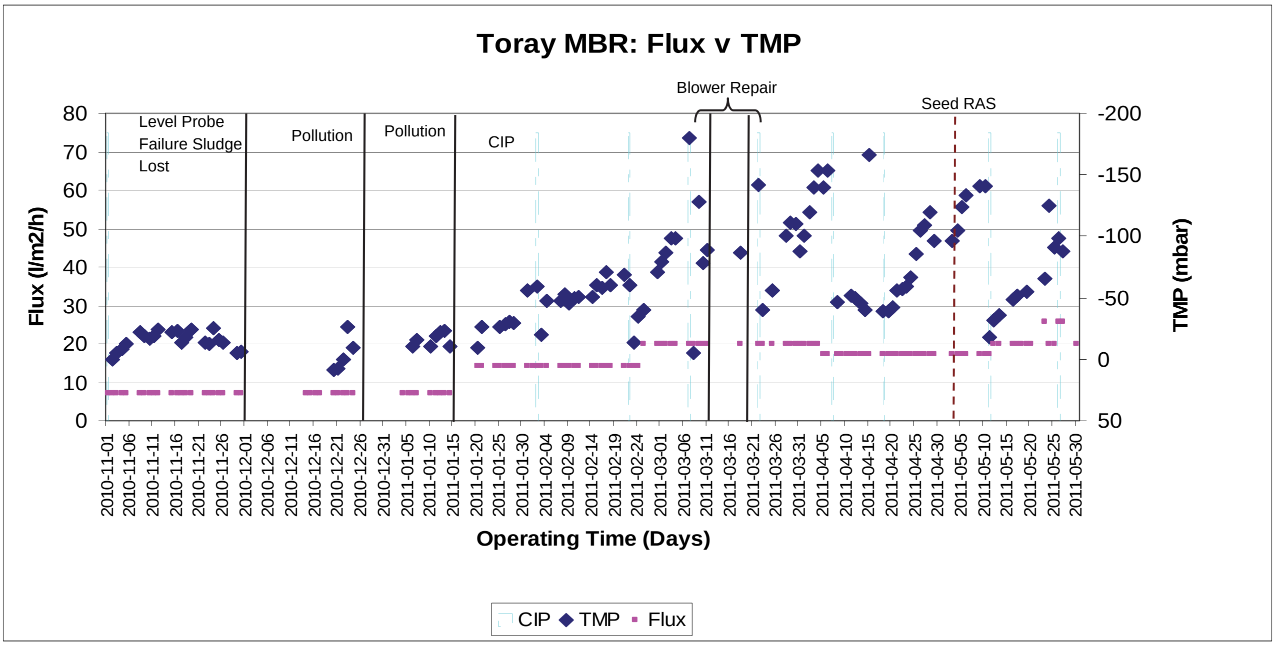


Figure 4.6: Toray MBR Flux v TMP (Nov 2010 - June 2011)

As shown in Figure 4.6, 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.

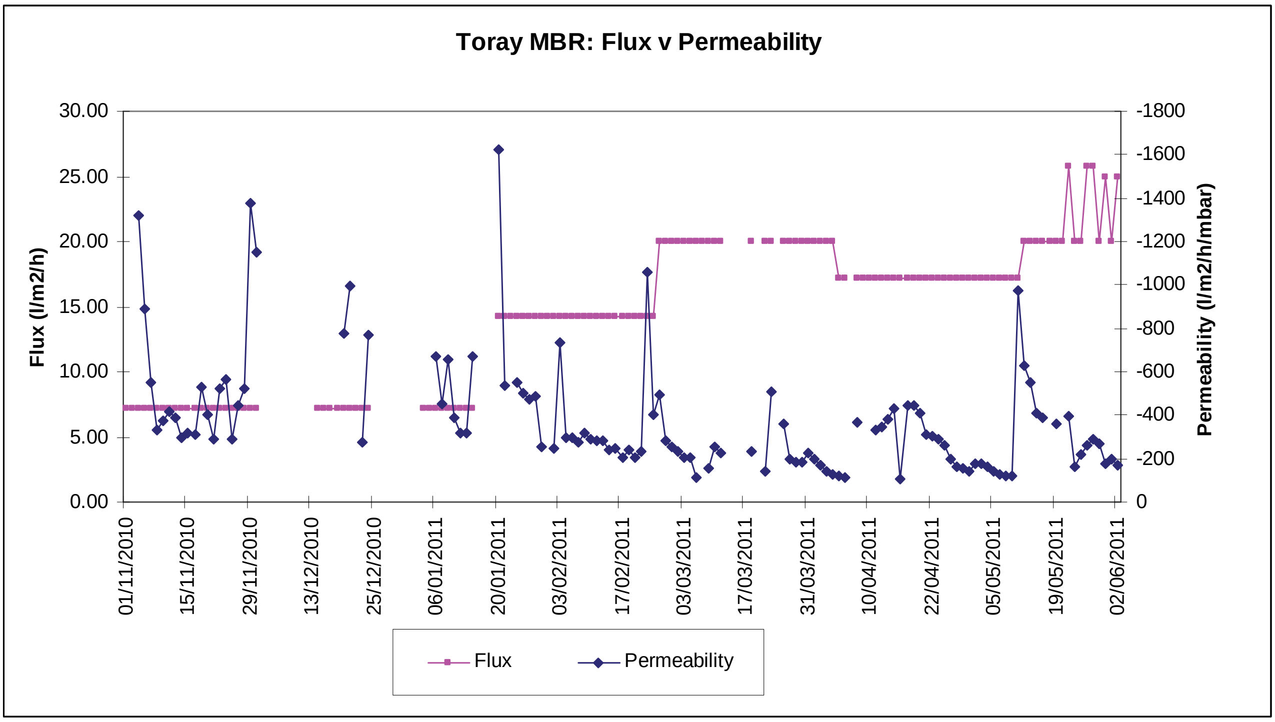


Figure 4.7: Toray MBR Flux and Permeability (Nov 2010 - June 2011)

The membranes were operated at a flux of 7 lmh (0.5 m^3/h) for 720 hours from 1st November 2010 to 30th November 2010. At this point a bioreactor water level probe malfunctioned resulting in no influent flow into the bioreactor. As a result the plant ran itself dry overnight. Attempts to reseed the plant failed due to the breakdown of an old diaphragm pump which was borrowed from the Darvill WWW. The procurement of a new submersible seeding pump took some time and following seeding normal operation was resumed on the 14th December 2010. 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. The bioreactor was reseeded with activated sludge on the 4th January 2011 and filtration was resumed at 7 lmh. Following a further 216 hours of operation another industrial pollution incident occurred on the 17th January 2010. 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) on the 20th January 2011. After 192 hours of operation a chemical clean was performed on the 2nd February 2011 in response to another pollution incident which took place on the 31st January 2011. Foaming and a drop in the MLSS to 1,000 mg/l were a consequence of the pollution, which is pictured in Annexure A-C.

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 the 22nd February 2011 when another CIP was performed after 336 hours of operation. The TMP at 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 on the 7th March 2011. Filtration was resumed but only for a few days as on the

11th March 2011 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 on the 25th March 2011. 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 on the 7th April 2011. The plant was operated at a flux rate of 17 for the next 192 hours. 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 on the 18th April 2011 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 on the 4th May 2011 in an attempt to increase the MLSS concentration. This was achieved and the MLSS concentration was increased from 6,688 to 11,136 mg/l. A maintenance clean was performed on the 10th May 2011 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 stable. The MLSS concentration during this period was within the manufacturer's 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 Section 4.4.

4.2.1.2 Toray Membrane Performance Evaluation

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

- <u>Continuous operation:</u> the plant was in operation without disturbances for a period of five days or more.
- <u>Correct MLSS range:</u> as the membranes are designed to operate at high MLSS concentration (>10,000 mg/l), the operational periods with low MLSS values are not applicable.
- <u>Stable biological process:</u> stability of the on-going biological processes is essential, to have the required sludge filterability. Sludge adaptation periods, rapidly changing MLSS concentrations and breakthrough events of toxic industrial streams all result in general changes in the sludge filterability.

The applied cleaning conditions varied 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 on the cleaning results. An estimate of the impact of the CIPs is given in Table 4.1 and a summary in Table 4.2.

Table 4.1: Toray MBR Cleaning in Place Results

Date of CIP	TMP (before) mbar	TMP (after) mbar	Permeability (before) lmh/bar	Permeability (after) lmh/bar
2/2/2011	-58.6	-19.4	244	736
22/2/2011	-60.6	-13.5	236	1058
7/3/2011	-180	-4.8	111	1166
22/3/2011	-145.5	-39.6	141	505
6/4/2011	-153.5	-46.3	111	370
18/4/2011	-166.3	-38.6	103	445
11/5/2011	-141.1	-17.6	121	974
Mean	-128.8	-25.7	152	750

Table 4.2: Toray MBR Cleaning in Place Summary

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

Based on the above figures, 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 January 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 4.3.

Table 4.3: 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	2/1/2011	21/1/2011	13	1	14	13	-26	-56	2.3	43	8978
2	14 lmh, low MLSS	4/2/2011	22/2/2011	19	1	14	13	-47	-93	0.8	119	3000
3	20 lmh, low MLSS	23/3/2011	6/4/2011	15	1.4	20	18	-39.6	-161	8.1	12	2655
4	17 lmh, rising MLSS	8/4/2011	14/4/2011	6	1.2	17	15	-46	-150	17.3	6	1500 to-15000
5	17 lmh, high MLSS	16/4/2011	28/4/2011	14	1.2	17	15	-38.5	-108	7.0	14	14800
6	17 lmh, middle MLSS	4/5/2011	9/5/2011	6	1.2	17	15	-99.6	-140	6.7	15	7885
7	20 lmh, high MLSS,9/11	11/5/2011	18/5/2011	8	1.4	20	16	-30	-55	3.1	32	12148
8	20 lmh, high MLSS,9/10	19/5/2011	23/5/2011	5	1.4	20	18	-55	-65	2.0	50	12665
9	Merge of periods 8 & 9	11/5/2011	23/5/2011	13	1.4	20	18	-30	-65	2.7	37	12954

Based on the filtration rates tested, the Toray design flux rates for municipal wastewater are not applicable at Darvill WWW. The frequent CIPs required suggest that the Darvill raw wastewater influent is not a standard municipal wastewater. The Darvill influent has an industrial component of about 10%. The results 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 cleaning every 4-5 weeks.

4.2.2 Norit Membrane Bioreactor System

4.2.2.1 Norit Membrane 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. On the 30th May 2010 the flux was increased to 35 lmh (1 m^3/h). On the 3rd June 2010 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 during June 2010, because of numerous operational problems. The plant was started again in July at a flux of 35 lmh, but normal operation was only obtained on the 12th July 2010. The plant was operated for 360 hours from the 12th - 27th July 2010, until a sudden increase in TMP beyond 0.5 bar tripped the plant. A CIP was performed, which comprised soaking the membranes in sodium hypochlorite (NaOCl) for two 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 28th July to the 12th August at which point it 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 the 13th August the plant was operated, with minor stoppages, for 1,272 hours to the 5th October 2010. 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 was restarted on the 6th October 2010 at a flux rate of 35 lmh. On the 12th October, after 144 hours of operation, the flux was increased to 37.5 lmh. On the 17th October the plant tripped due to high TMP. A CIP was performed (NaOCl soak) and filtration was resumed. Shortly afterwards a power outage at Darvill resulted in the plant tripping over the weekend (23-24th October), which resulted in sludge being left standing in the membrane vessel overnight. Filtration was resumed on the 25th of October at a relatively high TMP of 0.37 bar.

The plant was operated for a further 432 hours to the 11th November 2010, 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 these had to be imported from Holland, which resulted in the plant being shut down for over 2 months. Because the plant had been standing for some time (with potable water in the membrane) a CIP was performed before start-up on the 14th January 2011. The CIP involved two NaOCl soaks and drain sequences, one overnight NaOCl soak and an eight hour citric acid soak, completed with flushing and draining the membranes with potable water. Operation was resumed on the 17th January 2011 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 on the 21st January 2011. The plant continued to operate, with the flux rates being raised and lowered in response to operating conditions and increases in the TMP. The flux rate was kept at 30-42 lmh during this period of 1,008 hours of operation from the 17th January - 28th February 2011. At a 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). On the 1st March 2011 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 on the 18th March 2011. The plant was stopped for a CIP to be performed, following which filtration was resumed at a flux of 35 lmh on the 19th March 2011. 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 on the 23rd of March 2011. On the 25th March 2011 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 on the 6th April the permeate flux was set at 37.5 lmh, raised to 40 lmh on the 19th April and increased further to 45 lmh (1.3 m^3h^{-1}) on the 26th April 2011. Filtration continued at this flux rate until the 3rd May 2011. Over the 672 hours of operation the TMP had increased from 0.07 bar to 0.36 bar.

An MLSS above 10,000 mg/l, representative of a true MBR system, was required to perform the peak test analysis; hence on the 3rd May 2011 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 4,568 mg/l to 6,560 mg/l. The plant was restarted at 35 lmh and at a TMP of 0.28 bar on the 4th May 2011. On the 5th May the bioreactor was spiked with more RAS and this managed to increase the MLSS to 7,350 mg/l. The flux was increased to 45 lmh on the 9th May and filtration continued with the TMP rising gradually, reaching 0.33 bar on the 13th May 2011. Over the weekend of the 14-15th May an I/O (input/output) module malfunctioned and the plant tripped. The I/O module was replaced on the 17th May and filtration continued at 45 lmh (TMP = 0.22 bar) until the 23rd May when the flux was increased to 47 lmh (1.3 m^3/h). The bioreactor was spiked with RAS again on the 23rd May 2011 and this brought the MLSS to 10,844 mgl^{-1}, above the target MLSS concentration and high enough to undertake the peak tests. The results of the peaking experiment are discussed in Section 4.4. The flux data for the Norit MBR system is plotted against TMP and permeability in Figures 4.8 and 4.9.

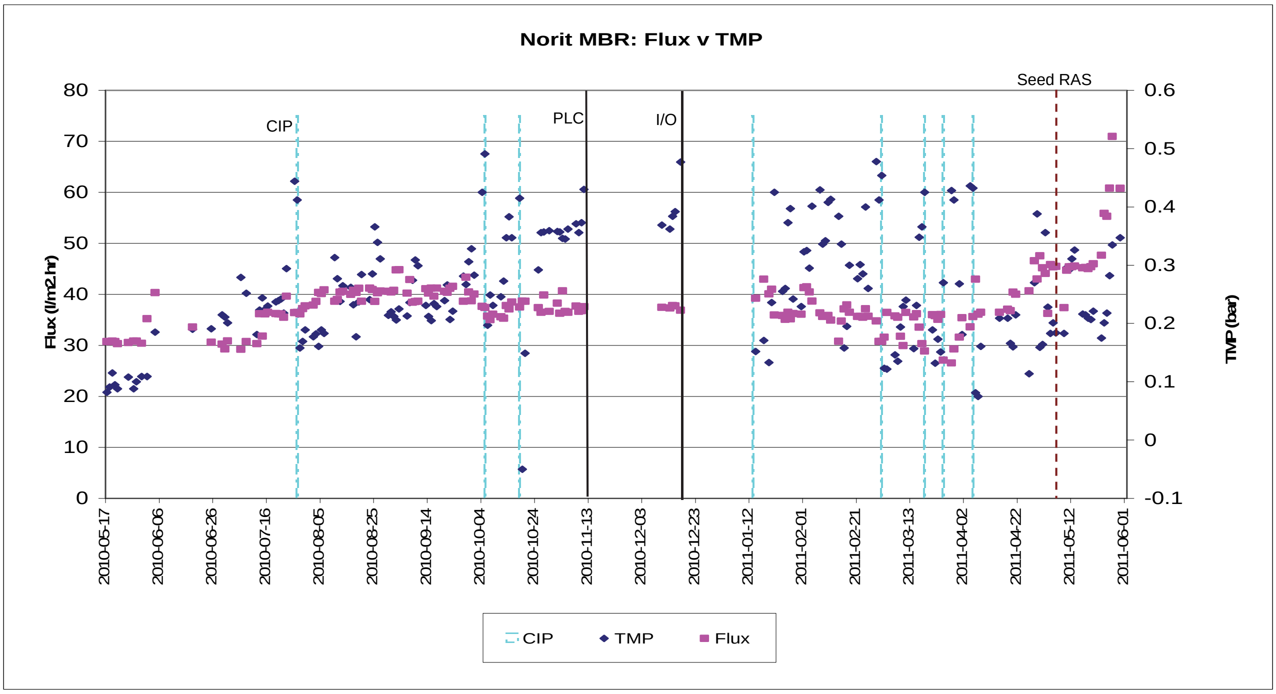


Figure 4.8: Norit Membrane Flux and TMP (May 2010 - June 2011)

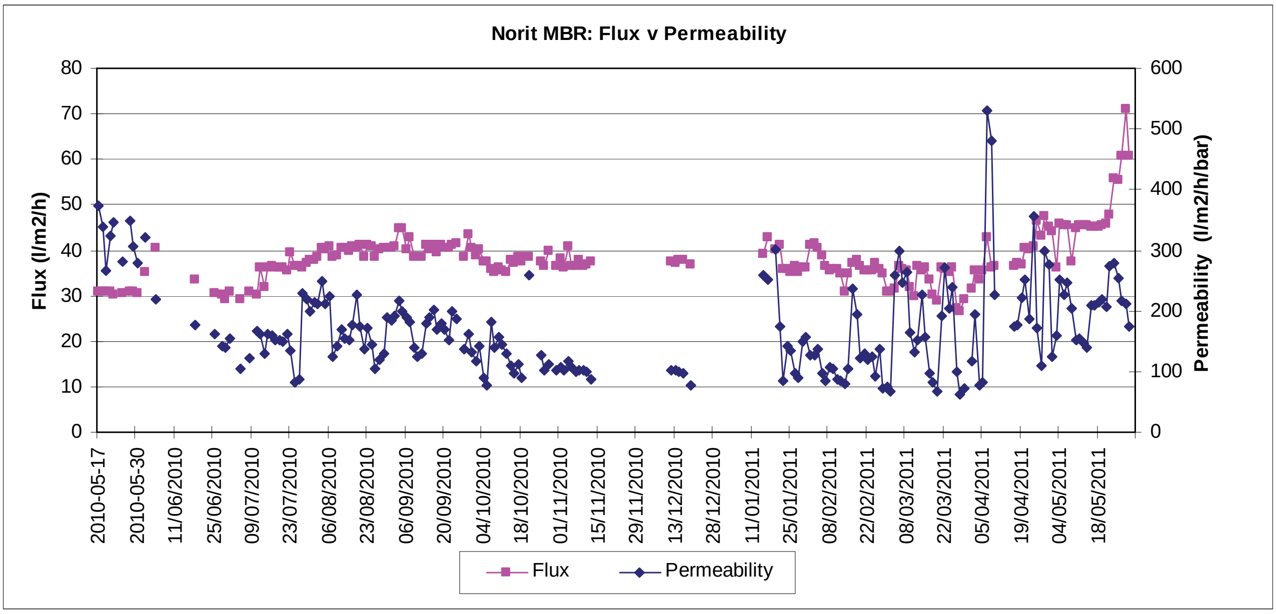


Figure 4.9: Norit Membrane Flux and TMP (May 2010 - June 2011|)

As shown in Figure 4.8, 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, and also, in 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 shutdowns, but it may also have reduced the effectiveness of scouring and thus increased the fouling potential.

As shown in Figure 4.9, the permeability dropped with time from May 2010 to November 2010, when operation was suspended temporarily. In 2011 the permeability decreased with increases in flux as expected. The surprising performance occurs towards the end of the tests when the MLSS concentrations were at their highest and approaching the Norit design MLSS concentration of >10,000 mg/l. The permeability can be seen to improve at this juncture even though the flux rates were increasing. It is proposed that the improvement in performance is a result of improved filterability associated with a more stable and concentrated biomass.

4.2.2.2 Norit Membrane Performance Evaluation

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

- <u>Continuous operation:</u> the plant was in operation without disturbances for a period of five days or more.

- MLSS range: as the membranes are designed to operate at high MLSS concentration (>10,000 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.

High MLSS, above 10,000 mg/l, was never obtainable 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 membrane performance. In the last month of operation the MLSS was maintained above 7,000 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 4.4, and a summary in Table 4.5.

Table 4.4: Norit Cleaning in Place Results

Date of CIP	TMP (before) Bar	TMP (after) bar	Permeability (before) lmh/bar	Permeability (after) lmh/bar
27/7/2010	0.412	0.158	88.36	229.15
5/10/2010	0.491	0.197	76.26	181.09
18/10/2010	0.415	0.05	90.40	259.31
2/03/2011	0.454	0.123	67.67	257.69
18/3/2011	0.425	0.189	68.05	190.97
5/4/2011	0.432	0.081	82.45	530.07
Mean	0.438	0.133	78.87	274.71

Table 4.5: 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 CIPs (mean)	0.133 bar
Permeability after CIPs (mean)	275 lmh/bar

Based on the above findings, it can be seen that the CIPs are resulting in an 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 4.6. The predicted average daily flux rate is 37.5 lmh and the predicted cleaning frequency with average daily flux is cleaning every 7-8 weeks.

Table 4.6: 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	13/7/2010	27/7/10	11	0.87	30	26	0.223	0.444	0.022	17	3,389
2	40 lmh, middle MLSS	23/8/2010	27/8/10	5	1.2	40	38	0.241	0.311	0.014	21	6,508
3	35 lmh, middle MLSS	6/10/2010	15/10/2010	8	1.0	35	32	0.197	0.347	0.018	17	5,922
4	35 lmh, low MLSS	4/3/2011	15/3/2011	8	1.0	35	32	0.122	0.231	0.014	21	3,296
5	45 lmh, middle MLSS	28/4/2011	2/5/2011	5	1.3	45	43	0.270	0.356	0.017	18	5,176
6	45 lmh, rising MLSS	4/5/2011	13/5/2011	8	1.3	45	43	0.183	0.326	0.018	17	7,276
7	45 lmh, stable MLSS	16/5/2011	20/5/2011	5	1.3	45	42	0.216	0.221	0.001	300	7,134

4.3 MBR WATER QUALITY PERFORMANCE

4.3.1 Toray MBR System

The quality of influent wastewater to the Toray MBR demonstration plant is summarized in Table 4.7. The influent was the same to both demonstration plants, which abstracted wastewater using submersible pumps from a 20 kl balancing tank. The balancing tank is fed with settled sewage from the inlet to the Darvill WWW activated sludge tanks.

Table 4.7: Toray MBR Influent Wastewater Quality

Parameter	Units	No. of Analysis	Average	Median	Minimum	Maximum	Std Dev
Alkalinity	mg/l CaCO3	67	221	224	102	352	45
Conductivity	mS/m	108	71	71	41	104	13
TDS	mg/l	65	403	381	50	696	110
Turbidity	NTU	108	107	87	20	478	70
SS	mg/l	112	81	68	15	282	48
BOD	mg/l	26	50	37	1	230	55
COD	mg/l	114	264	261	45	546	103

Coliforms	CFU/100 ml	19	9,065,800	3,105,000	19,600	24,190,000	9,419,476
Coliphages	PFU/100 ml	33	21,812	20,900	2,900	52,400	11,242
E.Coli	CFU/100 ml	32	2,451,323	1,986,000	30,000	9,210,000	2,438,453
TKN	mg/l	105	31	29	6	111	15
Ammonia	mg/l	115	18	19	5	30	5
Nitrite	mg/l	114	0.5	0.5	0.5	0.8	0
Nitrate	mg/l	116	0.67	0.5	0	9	0.7
Oil & Grease	mg/l	60	10	7	1.2	118	17
SRP	mg/l	114	1	1.3	0.1	7.3	0.9
TP	mg/l	69	4	2.7	0.9	32	5

Table 4.8 summarizes the permeate water quality from the Toray MBR plant. Some of these parameters are illustrated graphically in Figures 4.10-4.16. The permeate water quality results are discussed further in the following sections.

Table 4.8: 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

4.3.1.1 Particulate Removal

Figure 4.10 shows the influent and permeate turbidity concentrations for the Toray MBR pilot plant. The influent turbidity concentration 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. The project's permeate design specification and the manufacturer's specification for turbidity are both less than 1 NTU. The Toray membrane performed according to specification during the study period.

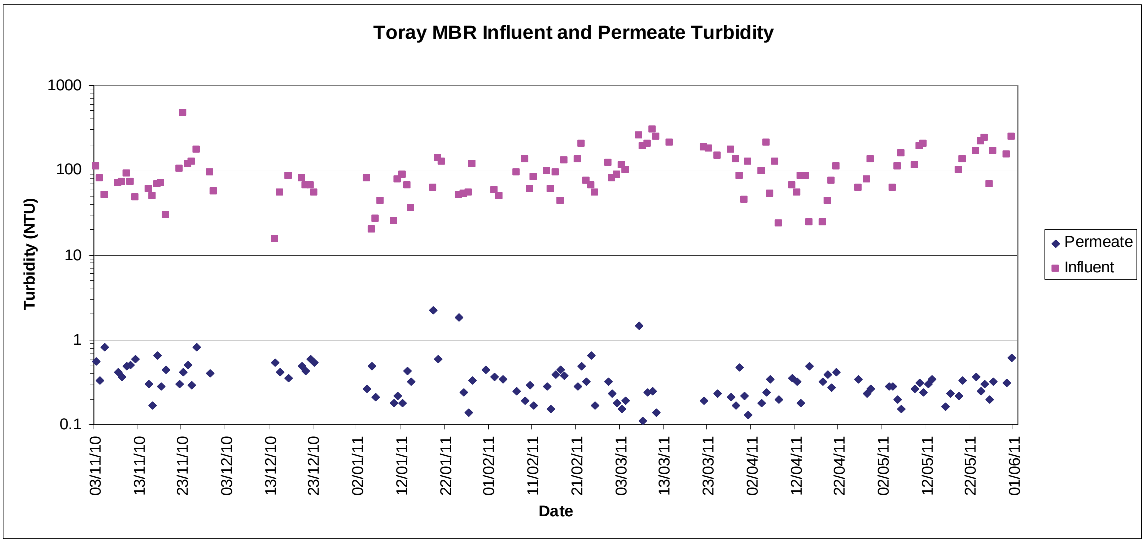


Figure 4.10: Toray MBR Influent and Permeate Turbidity (Nov 2010 - June 2011)

4.3.1.2 COD Removal

Figure 4.11 shows the influent and permeate COD concentrations for the Toray MBR pilot plant. The influent COD concentration 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. The permeate COD results are constrained by the Umgeni Water laboratory's detection limit of 20 mg/l. The project's permeate design specification of a permeate COD = 10 mg/l could not be determined because of the analytical limitations of COD measurement. The results are considered relatively good considering the disruptions to the demonstration plant biological process. The manufacturer's specification of COD less than 50 mg/l was very conservative and was comfortably achieved.

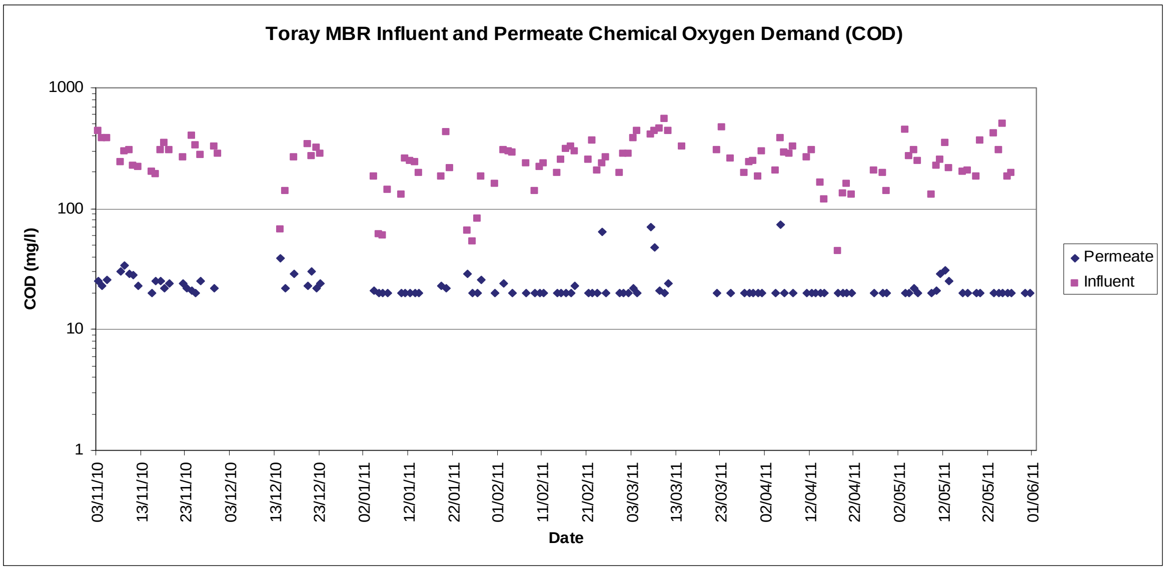


Figure 4.11: Toray MBR Influent and Permeate COD (Nov 2010 - Jun 2011)

4.3.1.3 Inorganic Nitrogen Removal

Figure 4.12 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 project's permeate design specification of < 0.5 mg/l NH_3 was thus achieved when the biological process was running effectively. 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 project's permeate design specification of < 5 mg/l NO_3 was thus not achieved. The denitrification process did not run as well as expected as is illustrated in Figure 4.13. Part of the reason for this may have been an over-oxygenation of the anoxic zone.

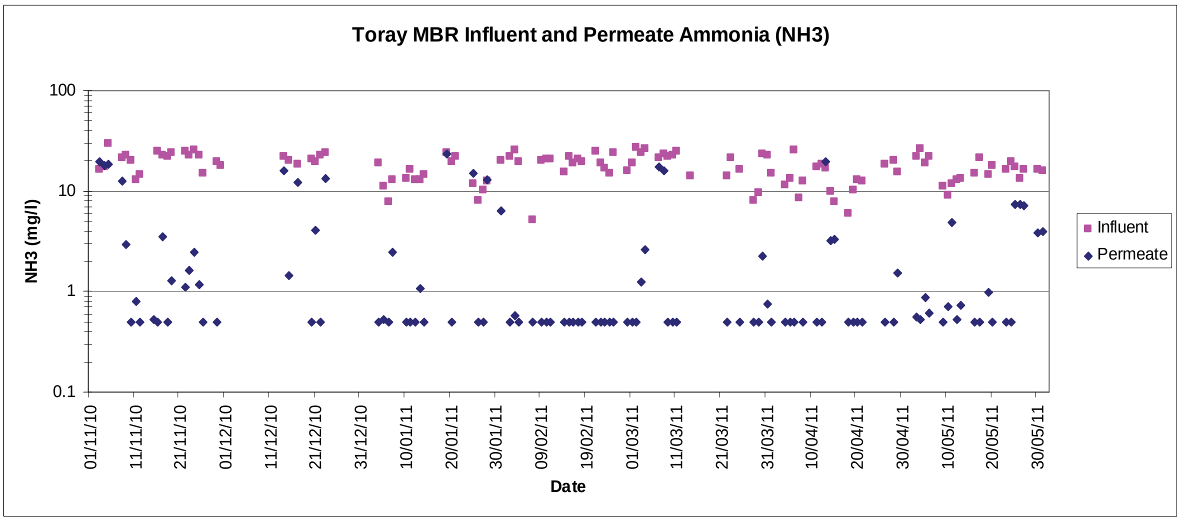


Figure 4.12: Toray MBR Influent and Permeate Ammonia (Nov 2010 - Jun 2011)

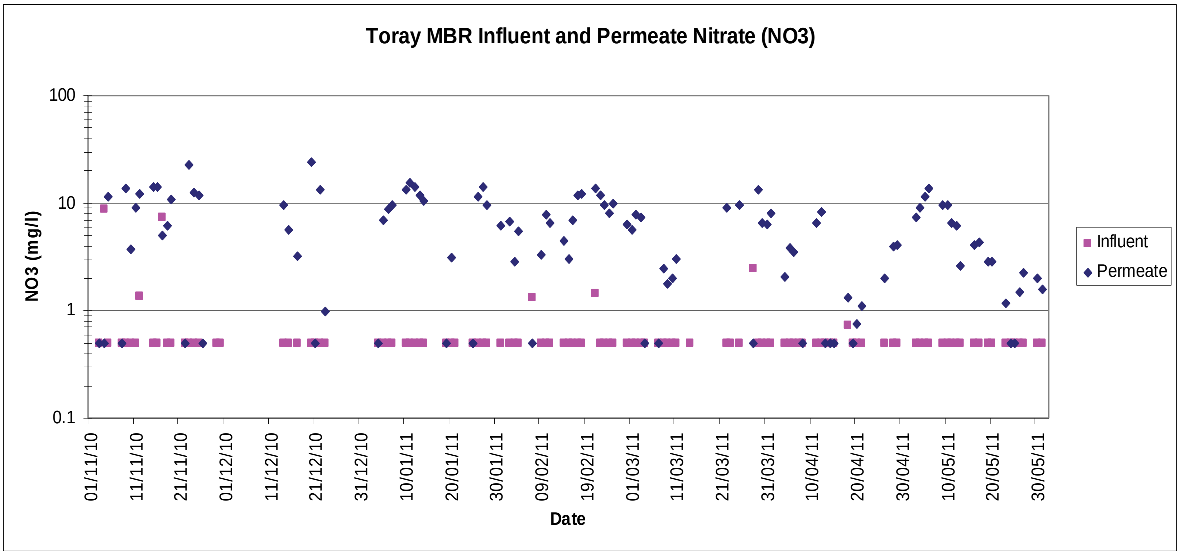


Figure 4.13: Toray MBR Influent and Permeate Nitrate (Nov 2010 - Jun 2011)

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 readily biodegradable COD needed for denitrification. An alternative flow scheme was devised to direct the oxygen-rich RAS to the aeration portion of the bioreactor, and take mixed liquor flow from the aeration tank to the anoxic zone. This scheme was unfortunately not carried out due to time and budget constraints.

4.3.1.4 Microbial Rejection

Figures 4.14-4.16 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 project's permeate design specification for total coliforms of < 10 CFU/100 ml was thus not achieved. Neither was the target of zero CFU/100 ml faecal coliforms (*E.coli*) and zero PFU/100 ml coliphages.

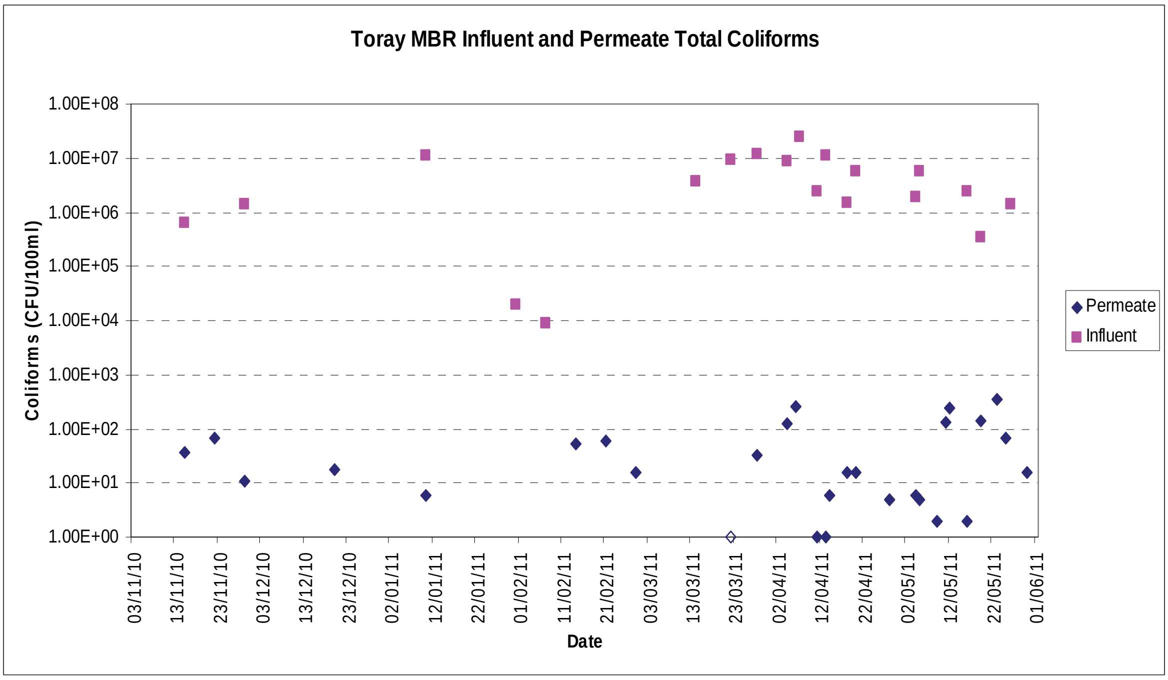


Figure 4.14: Toray MBR Influent and Permeate Total Coliforms (Nov 2010 - Jun 2011)

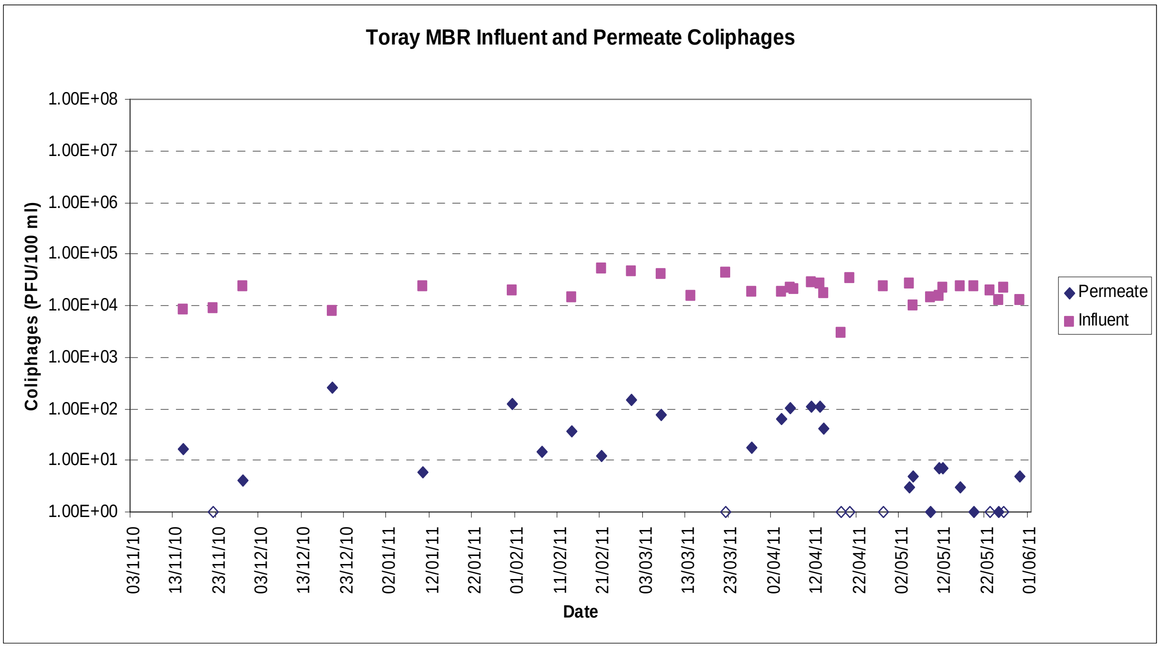


Figure 4.15: Toray MBR Influent and Permeate Coliphages (Nov 2010 - Jun 2011)

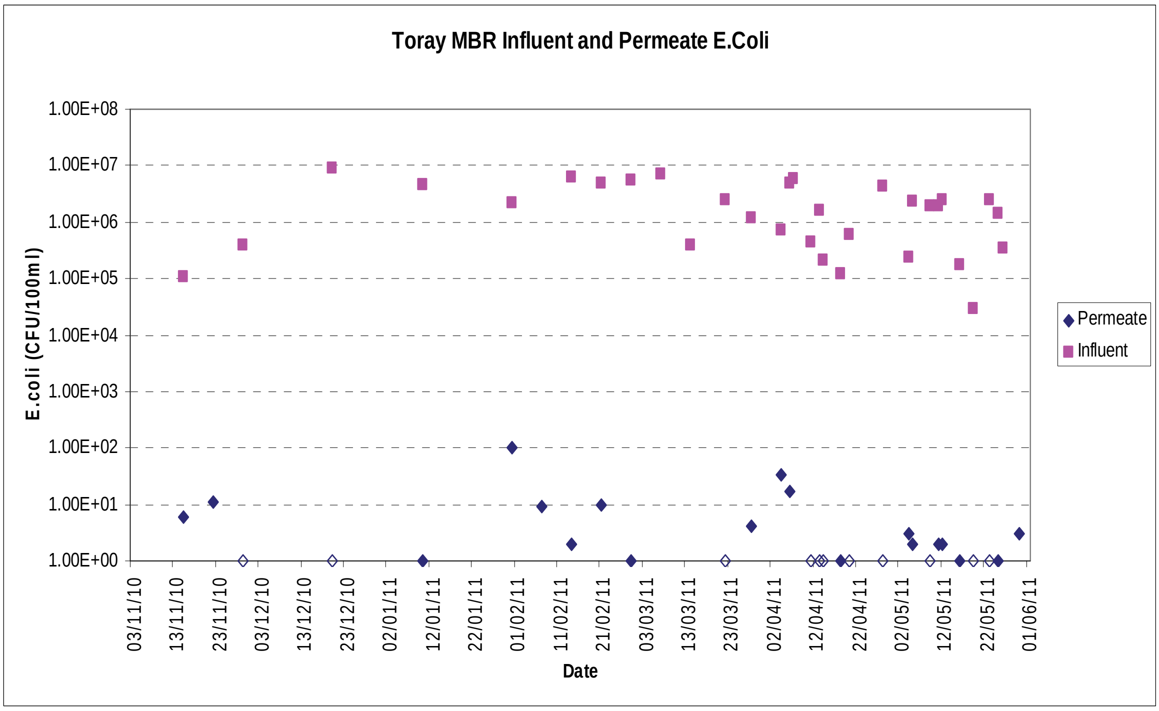


Figure 4.16: Toray MBR Influent and Permeate E.Coli (Nov 2010 - Jun 2011)

4.3.2 Norit MBR System

The quality of the influent wastewater to the Norit MBR demonstration plant is summarized in Table 4.9. The influent was the same to both pilot plants, which abstracted wastewater using submersible pumps from a 20 kl balancing tank. The Norit plant was operational for a longer period than the Toray plant and therefore the influent data has been collated separately.

Table 4.9: Norit MBR Influent Wastewater Quality

Parameter	Units	No. of Analysis	Average	Median	Minimum	Maximum	Std Dev
Alkalinity	mg/l	114	231	238	55	352	44
Conductivity	mS/m	38	73	53	7	345	71
TDS	mg/l	112	455	454	50	787	112
Turbidity	NTU	178	103	86	11	301	56
SS	mg/l	179	86	70	4	793	71
BOD	mg/l	38	73	53	7	345	71
COD	mg/l	188	309	301	45	874	126
Coliforms	CFU/100 ml	59	6,223,144	2,419,000	19,600	24,190,000	8,010,350
Coliphages	PFU/100 ml	59	21,295	1,2410	2,900	339,000	43,452
E.Coli	CFU/100 ml	57	1,691,133	1,203,000	7,000	6,870,000	1,873,866
TKN	mg/l	149	33	32	4	111	13

Ammonia	mg/l	186	21	22	0.5	57	7
Nitrite	mg/l	187	0.5	0.5	0	4	0
Nitrate	mg/l	187	0.5	0.5	0.5	5	0
Oil & Grease	mg/l	102	11	7	1.2	118	15
SRP	mg/l	181	2	1.8	0.1	7	1
TP	mg/l	117	4	3.2	0.5	32	4

Table 4.10 summarizes the permeate water quality from the Norit MBR. Some of these parameters are illustrated graphically in Figures 4.17-4.23. The permeate water quality results are discussed further in the following sections.

Table 4.10: 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	322	11	0	2,419	699
Coliphages	PFU/100 ml	59	4.7	0	0	153	25
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

4.3.2.1 Particulate Removal

Figure 4.17 shows the influent and permeate turbidity concentrations for the Norit MBR demonstration plant. The 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 project's and the manufacturer's permeate design specification for turbidity are both less than 1 NTU. The Norit membrane performed according to specification during the study period.

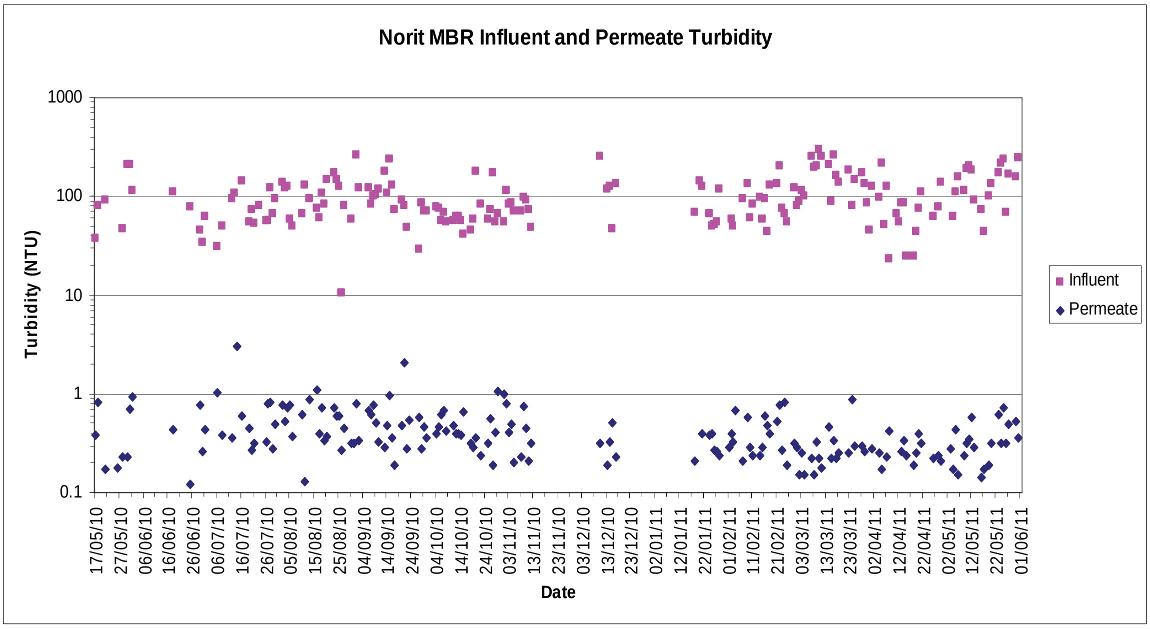


Figure 4.17: Norit MBR Influent and Permeate Turbidity (May 2010 - Jun 2011)

4.3.2.2 COD Removal

Figure 4.18 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. Umgeni Water laboratory's detection limit for COD is 20 mg/l. Norit did not provide a specification for COD in the permeate as COD removal is for the most part dependent on the performance of the biological process and not the membrane.

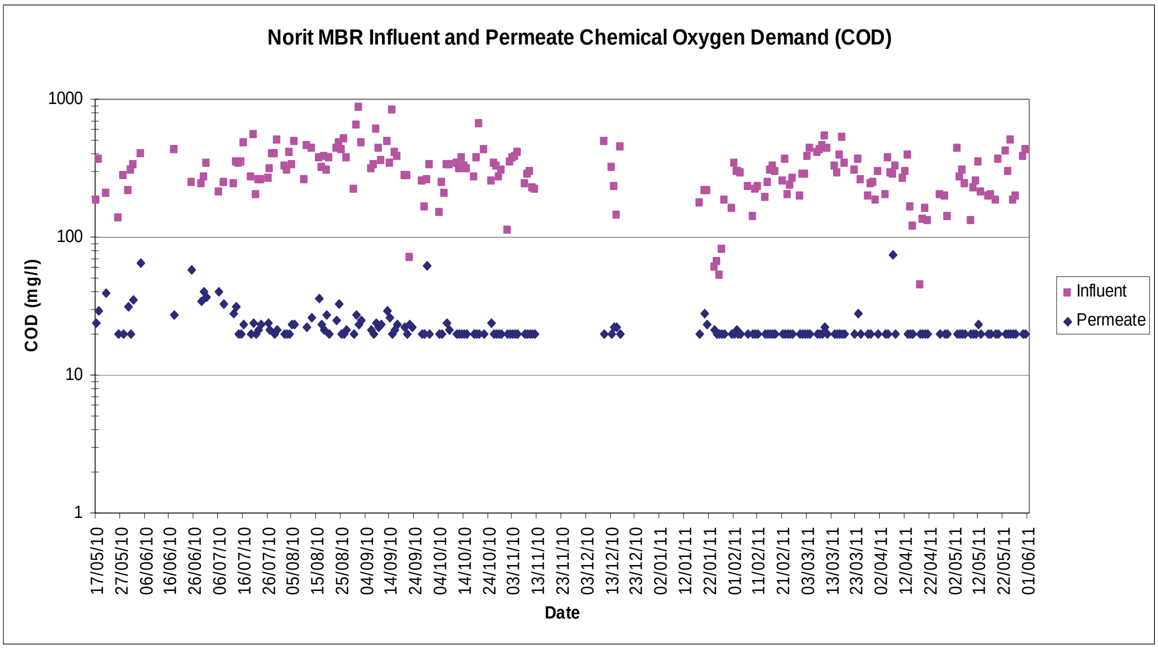


Figure 4.18: Norit MBR Influent and Permeate COD (May 2010 - Jun 2011)

4.3.2.3 *Inorganic Nitrogen Removal*

Figure 4.19 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 deigned 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. The project's 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 in 2011. This improvement in nitrification is thought largely to be as a result of greater reliability in the pilot plant operation (less downtime) as well as fewer pollution incidents (biomass loss).

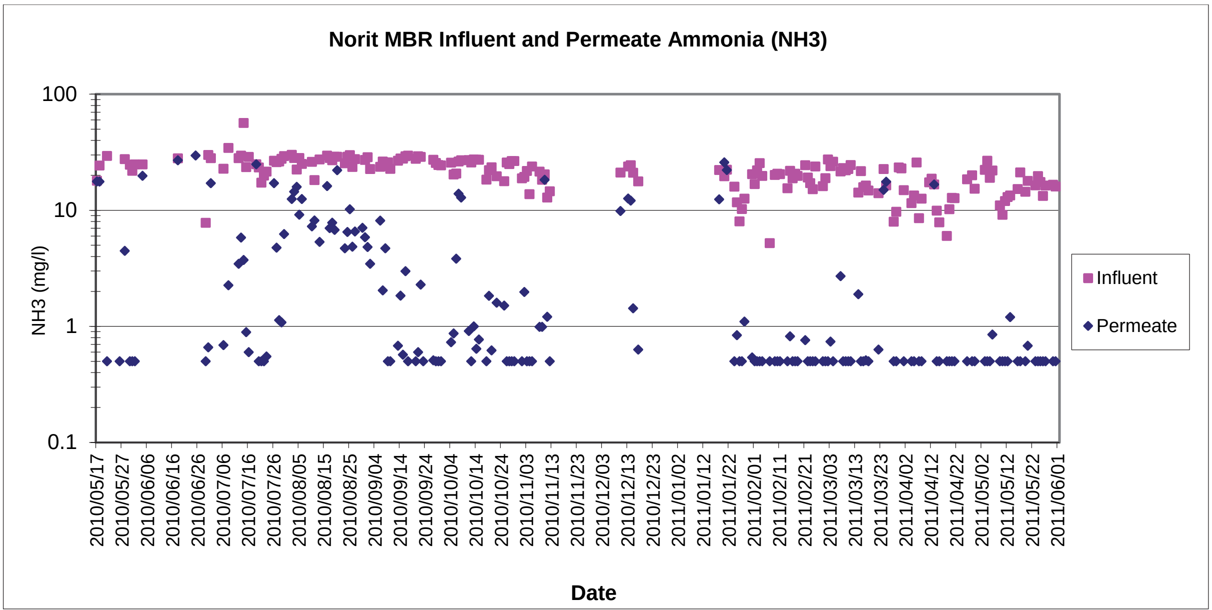


Figure 4.19: Norit MBR Influent and Permeate Ammonia (May 2010 - Jun 2011)

The permeate nitrate (NO_3) concentration ranged from 0.5-15.7 mg/l with a median value of 2.5 mg/l. The project's permeate design specification of < 5 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 4.20.

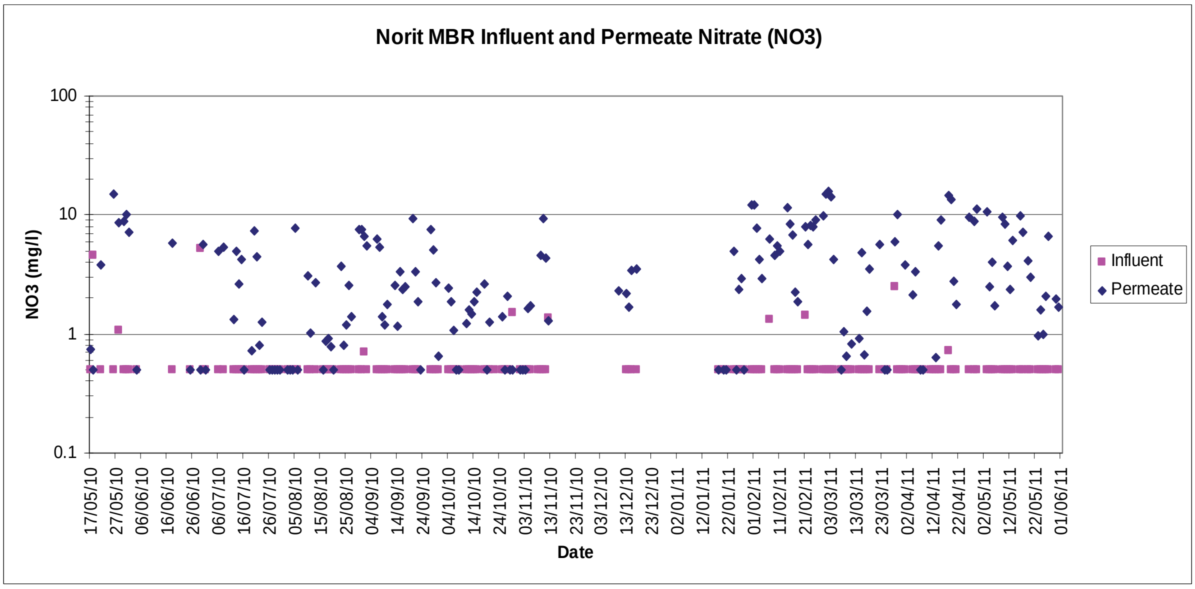


Figure 4.20: Norit MBR Influent and Permeate Nitrate (May 2010 - Jun 2011)

4.3.2.4 Microbial Rejection

Figures 4.21 to 4.23 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.

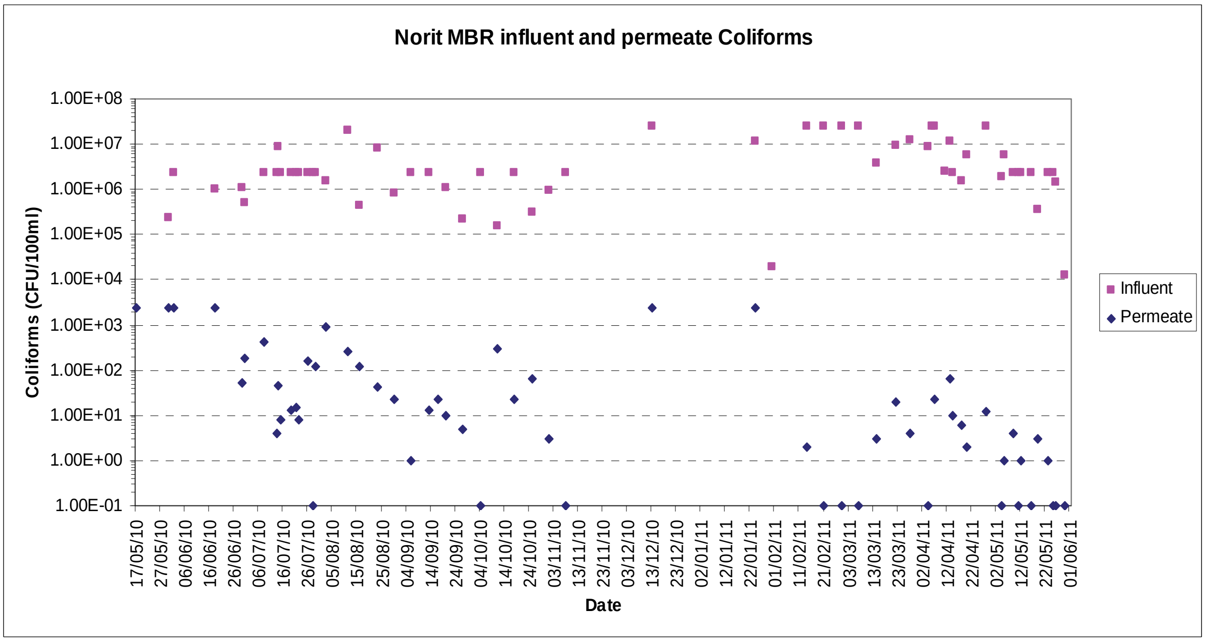


Figure 4.21: Norit MBR Influent and Permeate Total Coliforms (May 2010 - Jun 2011)

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 project's permeate design specification for total coliforms of less than 10 CFU/100ml was almost achieved and the target of zero CFU/100 ml faecal coliforms (*E.coli*) and zero PFU/100 ml coliphages was achieved. The faecal coliform and coliphage levels in the Norit MBR permeate were found to be below the detection limit for most of the samples collected during the normal operation of the plant.

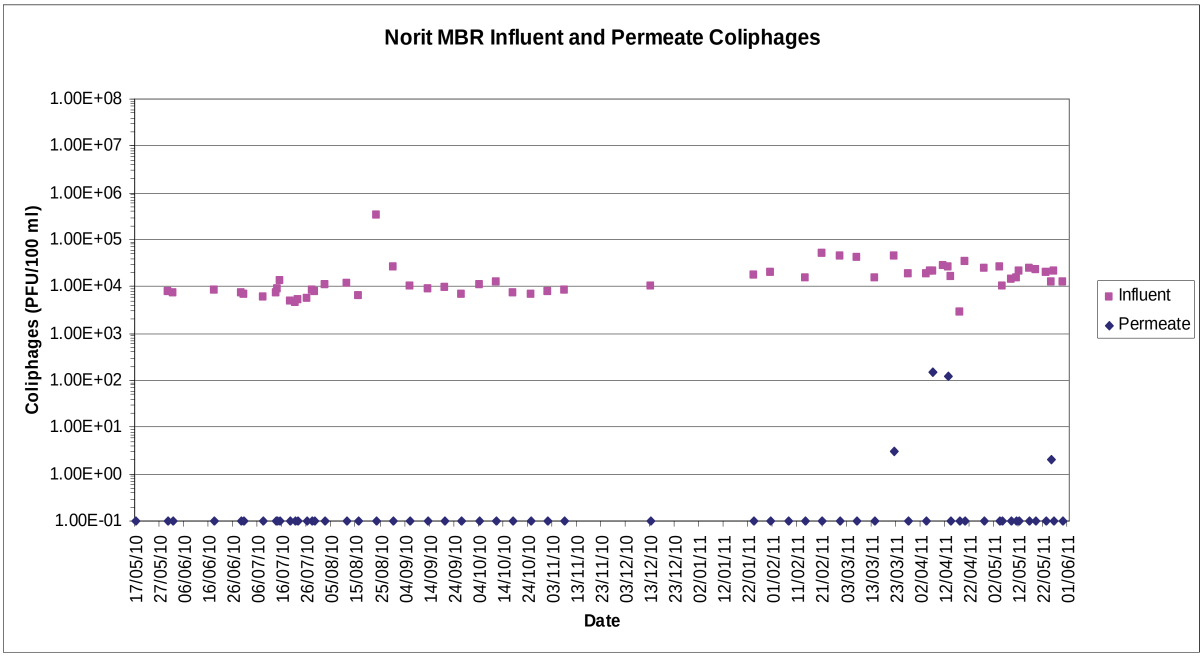


Figure 4.22: Norit MBR Influent and Permeate Coliphages (May 2010 - June 2011)

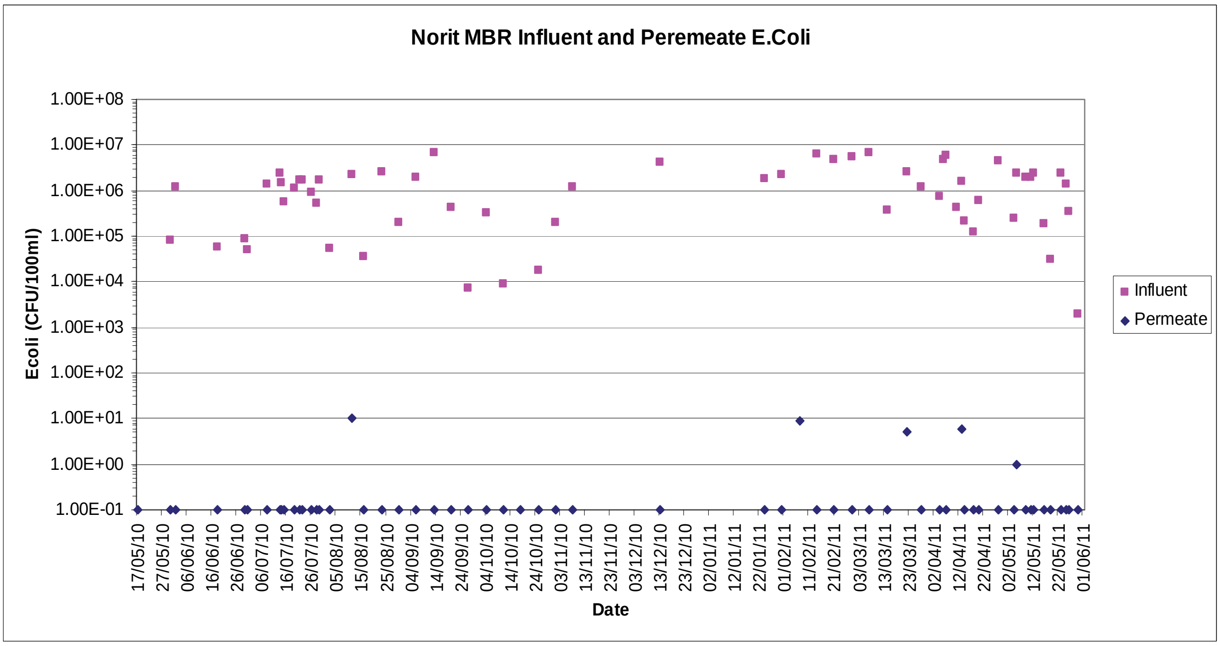


Figure 4.23: Norit MBR Influent and Permeate E.Coli (May 2010 - June 2011)

4.4 PEAKING STUDY

The city of Pietermaritzburg has separate sewage and drainage systems; however, studies have shown that the sewers suffer from high levels of wet weather infiltration (Actus Integrated Management, 2008). Wet weather flows can reach as high as six to eight times the average dry weather flow. 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 two to three times the average (Chapman et al., 2006). All wastewater has to pass through the MBR membranes to be considered treated water. As a result, MBRs 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 eight 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 nine day peaking study was conducted on the Toray MBR system that involved running the Toray MBR plant at a peak flux for 24 hour 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 nine 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 made it possible to assess the MBR membrane fouling rates at higher (peak) fluxes and to see if operating pressures (TMP) stayed within the supplier's recommendations.

4.4.1 Toray MBR

4.4.1.1 Operating Parameters

The supplier-recommended operating parameters for the Toray MBR system during the peaking study are specified in Table 4.11. 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 4.11: 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, is provided in Table 4.12.

Table 4.12: Operating Parameters for Toray MBR during Peaking Study

Description	Start	End	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	23/5/2011	24/5/2011	24	1.8	25	-65	-125	-60		12,848
Reduced Flux	24/5/11	25/5/2011	24	1.4	20	-94	-97	-2		12,284
Reduced Flux	25/5/2011	26/5/2011	24	1.4	20	-97	-98	-1		12,824
Peak Test 2	26/5/2011	26/5/2011	12	1.8	25	-98	-151	-53	3 hours NaOCl	12,148
Peak Test 2	26/5/2011	27/5/2011	12	1.8	25	-88	-101	-13		12,148
Reduced Flux	27/5/2011	30/5/11	72	1.4	20	-71	-74	-3		12,140
Peak Test 3	30/5/2011	31/5/2011	24	1.8	25	-74	-157	-83		12,200
Reduced Flux	31/5/2011	1/6/2011	24	1.4	20	-103	-103	0		12,150
Peak Test 4	1/6/2011	1/6/2011	22	1.8	25	-103	-156	-47		12,130

4.4.1.2 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 4.24). This indicates that the system was not operating in a stable condition. In particular, it is noted in Figure 4.24 that for peak test number 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 operation at a reduced flux was resumed, the permeability did not return to 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 predicted peak flux rate based on the operating environment at Darvill WWW is therefore 20 lmh for continued sustainable operation.

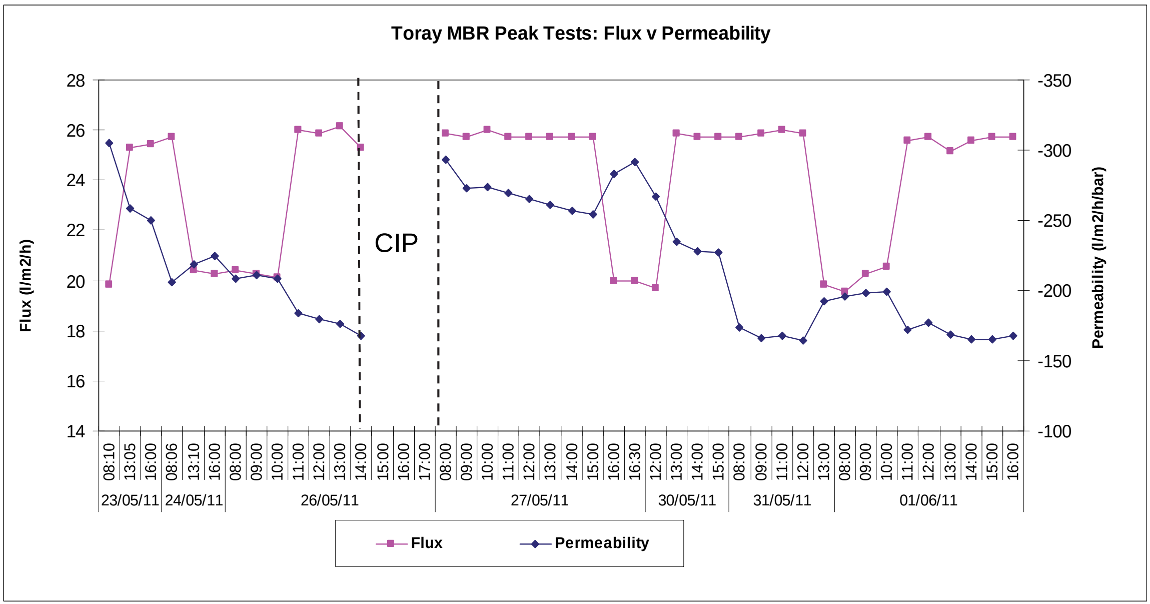


Figure 4.24: Toray MBR Peak Tests Flux and Permeability

4.4.2 Norit MBR

4.4.2.1 Operating Parameters

The supplier-recommended operating parameters for the Norit MBR system during the peaking study are specified in Table 4.13. 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 was performed for 15 seconds, which was 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. The daily peaking schedule for the system is shown in Table 4.14.

Table 4.13: 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^3h)	420	10	300	13	Continuous	11
Peak 1	55 (1.6 m^3h)	420	10	300	13	Continuous	9
Peak 2	60 (1.7 m^3h)	420	10	300	13	Continuous	8
Peak 3	65 (1.9 m^3h)	420	10	300	13	Continuous	7
Maximum	70 (2.0 m^3h)	420	10	300	13	Continuous	7

Table 4.14: Operating Parameters for Norit MBR during Peaking Study

Description	Start	End	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	24/5/2011	24/5/2011	6	1.3	45	0.198	0.191			10,844
Peak	24/5/2011	26/5/2011	43	1.6	55	0.221	0.261	0.04		11,272
Peak	26/5/201	27/5/2011	24	1.7	60	0.31	0.314	0.003		10,848
Maximum	27/5/2011	27/5/2011	5	2.0	70	0.311	0.443	0.132		10,636
Reduced	27/5/2011	29/5/2011	42	1.7	60	0.319	0.309			9,776
Peak	30/5/2011	30/5/2011	3	1.9	65	0.358	0.348			9,192
Reduced	30/5/2011	31/5/2011	20	1.6	55	0.243	0.3660	0.123		9,092
Peak	31/5/2011	31/5/2011	3	1.9	65	0.291	0.279			9,100
Reduced	31/5/2011	1/6/2011	18	1.6	55	0.255	0.359	0.104		9,050

4.4.2.2 Membrane Performance

On the 24th May 2011, the flux rate was increased from 45 lmh (1.3 m^3) at 0.18 bar to 55 lmh (1.6 m^3). On the 25th May, at 55 lmh, the TMP had increased to 0.22 bar. On the 26th May, the flux was increased to 60 lmh (1.74 m^3) and the TMP increased to 0.28 bar. The flux was then increased to 70 lmh (2 m^3), the maximum possible flux for the membrane module, on the 27th May. The MLSS concentration at this time was 10,636 mg/l, just above the target concentration. The flux was kept at 70 lmh for 5.30 hours and then reduced 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, on the 30th May 2011, 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 kept between 55 and 65 lmh for the remainder of the test. The permeability remained reasonably constant through this period as did the TMP. A plot of the impact of the peak tests on the permeability is given in Figure 4.25.

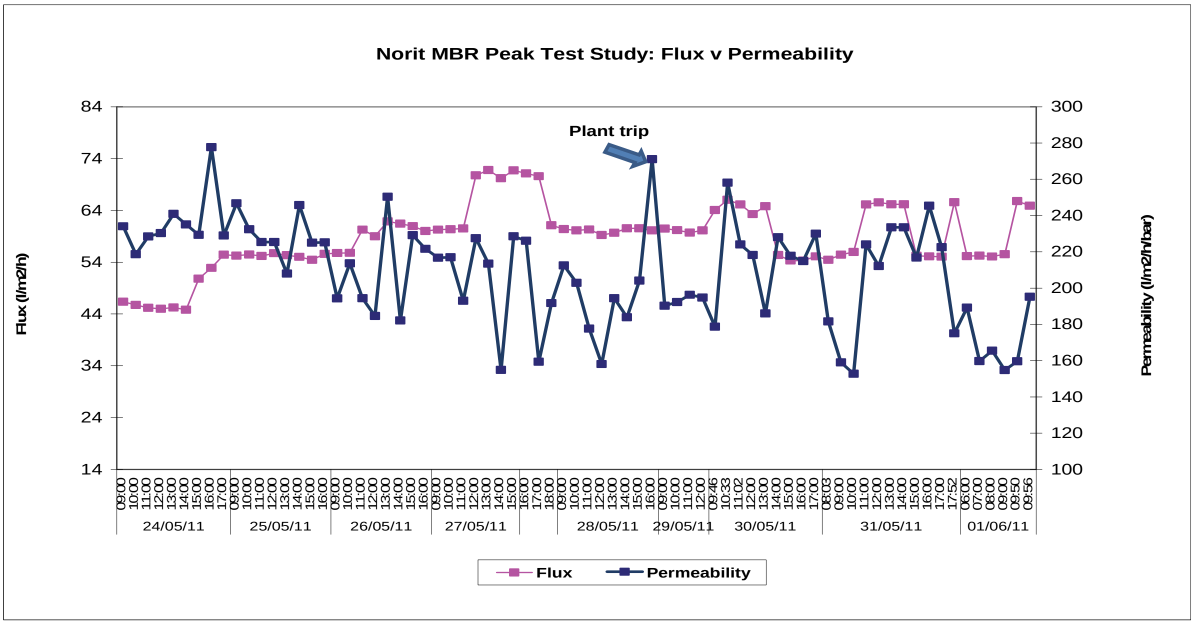


Figure 4.25: Norit MBR Peak Test Flux and Permeability

A second set of peak tests was started on the 1st June 2011 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 could be managed by a controlled drop in flux. The predicted average daily flux for the Norit membrane is 37 lmh and the peak flux is 45 lmh, or 1.2 times the average daily flux.

4.5 MBR PILOT PLANT OPERATING EXPERIENCE

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 available so that the plants could be operated from the operator's PC. The pilot system required operator attention for sludge wasting since the sludge wasting had to be done manually. Since there was no flowmeter 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 became 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 and cleaning from time to time.

The blower in the biological reactor was problematic. As a result, the operators were unable to adjust the aeration to maintain the target 1-2 mg/l DO level in the aerobic tank. Although a variable speed drive, 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.

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 onsite using a touch screen, 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 was shipped from Singapore where it had been used previously at a trial. 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 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. 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 applicable 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 onsite PLC was simple and effective. Remote access via the internet added flexibility of operation, especially on weekends and public holidays. It also allowed specialist 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.
- Online instrumentation saved time and provided back-up to routine manual measurements. Some instrumentation, however, gave problems and the submerged instrumentation needed cleaning and calibration every few months. The online 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 back-up system or manual checking. Incorrect level readings resulted in the bioreactor being drained of all MLSS and, on a separate occasion, in the settled sewage feed tank overflowing.
- One of the biggest problems was the availability of instrumentation technicians. No formal arrangements had been made in this regard with Umgeni Water and thus any assistance requested was subject to approval and the availability of the technicians. As they were naturally busy, and the pilot plants were not a priority, the result was 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 MBRs 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.

4.6 MBR PILOT STUDIES PERFORMANCE COMPARISON

Performance of the MBR systems tested at Darvill was compared to similar MBR pilot studies conducted around the world as detailed in Chapter two.

4.6.1 Permeate Water Quality

Tests conducted at Point Loma in San Diego and Bedok in Singapore recorded similar permeate water quality results. In both case studies the municipal wastewater was of similar character to 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, as presented in Table 4.15.

Table 4.15: MBR 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 (Av/Med)**	**Norit (Av/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*	-
BOD_5 (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)
NO_3 (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 in 2012

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 were not as low as those recorded at Point Loma. As the Toray and Norit membranes used are the same at both sites the difference can probably be attributed to instrumentation measurement accuracy. The permeate BOD, COD and TOC are all similar. The ammonia concentrations measured in the effluent of all systems were low (i.e. 0.2 to 0.71 mg/l-N), indicating that the systems achieved complete nitrification. Understandably, 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 Darvill Norit membrane performed exceptionally well and recorded zero median values for *E.coli*and coliphages.

The Bedok MBR pilot plant trials led to the construction of a full-scale MBR reclamation plant at Ulu Pandan. The wastewater feed to the MBR pre-treatment is roughly 90% domestic and 10% industrial, which is the same proportional mix as Darvill and therefore provides an opportunity for the assessment of results at full scale. Submerged Zeeweed ZW500c cassettes, operating at a flux of 25 lmh, produced a high final permeate water quality. In table 4.16, the water quality results from the Darvill MBR pilot plant and Ulu Pandan are compared. The Ulu Pandan plant outperformed the Darvill pilot plant with respect to reduction in TOC and the rejection of bacteria. This may to some extent be attributed to contamination of the permeate line at Darvill, which is not chlorinated. Very similar performance was obtained in terms of denitrification and phosphorous removal. This is very interesting as it shows that even on a plant such as Ulu Pandan where operational efficiency is a priority, biological nutrient removal can still be difficult.

Table 4.16: Permeate Water Quality Performance Comparison

Parameter	Units	Ulu Pandan (Zeeweed)	Darvill (Toray)
BOD_5	mg/l		
COD	mg/l		
TOC	mg/l	4.8	6.2
TSS	mg/l		
Turbidity	NTU	0.02	0.37
TKN	mg/l		
NH_4-N	mg/l		
NO_3-N	mg/l	6.3	6.3
Alkalinity	mg/l as $CaCo_3$		
Coliforms	CFU/100 ml	<1	60
MLSS Temperature	^0C		
Total Phosphate as P	mg/l	3.3	2.6
pH			

4.6.2 MBR and 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 the submerged MBR systems measured between 17 and 27 lmh whereas that for the external MBR system measured between 37.5 and 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.

To determine the performance of the MBR systems at peak flux, six day and nine day peaking studies were conducted on each MBR system, at both Point Loma (2009) and Darvill. 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 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 in the Norit external MBR system. 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) point 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.

CHAPTER 5: CONCLUSIONS

Based on the operating experience and recorded MBR performance, the predicted average flux for the submerged Toray MBR system is 17 lmh, whereas the predicted average flux for the external Norit MBR system is 37.5 lmh. The predicted peak flux for the Toray membrane is 20 lmh whereas for the Norit external membrane it is 45 lmh. The predicted cleaning frequency is 5-6 weeks for the Toray MBR and 7-8 weeks for the Norit MBR. The calculated sustainable flux rates are lower than those expected and reported by the membrane manufacturers, and the cleaning frequencies are higher. It was concluded that the industrial component of the influent sewage was having a marked effect on membrane flux and permeability. The consistent reduction in permeability, and corresponding increase in TMP in both membrane systems can most likely be attributed to membrane fouling, both inorganic and organic. The recovery of permeability following chemical cleans with sodium hypochlorite and citric acid is evidence of these foulants being removed.

Membrane flux for both systems was negatively affected by operational conditions. Frequent breakdowns, power failures and pollution incidents combined to make the operating conditions very unstable. A major consequence of this was the inability of the biological system to maintain MLSS concentrations above the targeted >10,000 mg/l. Low MLSS, at < 7,000 mg/l, resulted in low filterability of the sludge; increased fouling and a decrease in permeate water quality. This was particularly evident at higher flux rates. Some improvement in the performance of the MBR systems was noticeable once the MLSS were maintained above 10,000 mg/l; higher sustainable flux rates were maintained with only slight increases in TMP over time. This was especially evident during the Norit peak flux assessment where the TMP remained constant despite a flux rate in the 55-65 lmh range. Keeping the MLSS concentration above 10,000 mg/l was, however, difficult and therefore it was not possible to determine how long the higher flux could be maintained sustainably.

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

The Norit membrane performed slightly better than the Toray membrane in terms of microbial rejection, achieving zero values in the permeate for both faecal coliforms and coliphages. This was expected as the pore size of the Norit (0.03 µm) is less than that of the Toray (0.08 µm). Performance in removal of suspended solids was the same, with permeate NTU = 0.3 for both membranes.

The permeate water quality from both MBR systems met, or was close to, the stated target water quality objectives, which were established through a literature search and discussions with the MBR demonstration plant suppliers. Notable exceptions were found in relation to the permeate chemical oxygen demand (COD = 20 mg/l) in both plants, and the nitrate values (NO_3 = 6.5 mg/l) in the Toray plant permeate. The target COD value of <10 mg/l may, however, have been reached, but could not be assessed because of a COD detection limit of 20 mg/l at the Umgeni Water laboratory. The denitrification process in the Toray bioreactor was negatively affected by over oxygenation. 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 needed for denitrification. The MBR demonstration plants' performance in terms of biological nutrient removal (COD, NH_3) and membrane rejection (SS, coliforms) was also comparable to other demonstration plants referenced in the literature.

The Darvill pilot study showed that MBR technologies, both submerged and external (sidestream), produce a high standard permeate water quality. The Darvill results are replicated or exceeded in other MBR pilot plant studies such as those undertaken at Point Loma and Bedok. The Point Loma trials used the same MBR technologies (Norit and Toray), and this provides confidence in the performance of these particular MBRs under different operating conditions.

The Bedok trials illustrated the slightly superior performance of MBR over conventional secondary treatment with downstream UF polishing. As a result, a full-scale plant was constructed at Ulu Pandan by the Singaporean PUB. The treatment train of MBR-RO at Ulu Pandan reclamation plant is trialled in Phase 2 of this project.

The MBR technologies trialled at Darvill verified what has previously been presented in the literature both at pilot and full-scale MBR plants. MBR removes contaminants that would have an adverse effect on the operation of advanced treatment technologies e.g. turbidity. Trials at Ulu Pandan have shown that MBR is in fact superior to conventional treatment with UF polishing. MBR is thus suitable as a pre-treatment with technologies such as RO that are very sensitive to water quality.

The MBR technology would thus be recommended for use as a pre-treatment step for advanced wastewater treatment technologies.

The Toray MBR pilot plant was selected for further studies as it has been proven to be operationally reliable and easy to operate. The Norit MBR pilot plant was decommissioned. The next phase of studies involves testing of advanced treatment technologies at a laboratory scale, using the MBR effluent as feed water.

REFERENCES

1. Actus Integrated Management (2008) Msunduzi Municipality Wastewater Network Overview.

2. Adham S and Gagliardo P (1998) Membrane Bioreactors for Water Re-purification – Phase I. Desalination Research and Development Program. Report No. 34. Project No. 1425-97-FC-81-30006. U.S. Department of Interior, Bureau of Reclamation.

3. Chapman S, Leslie G and Law I (2006) Membrane Bioreactors for Municipal Wastewater Treatment – An Australian Perspective. Available at www.membrane.unsw.edu.au.

4. Cicek N (2003) A Review of Membrane Bioreactors and their Application in the Treatment of Agricultural Wastewater. *Canadian Biosystems Engineering.* Volume 45.

5. DeCarolis J and Adham S (2007) Performance Investigation of Membrane Bioreactor Systems During Municipal Wastewater Reclamation. *Water Environment Research.* Volume 79 No. 13.

6. DeCarolis J, Hirani Z and Adham S (2009) Evaluation of Newly Developed Membrane Bioreactor Systems for Water Reclamation. Desalination and Water Purification Research and Development Programme. Report No. 147. Project No. 105-FC-81-1157. U.S. Department of Interior, Bureau of Reclamation.

7. Desalination and Water Reuse (2011) How has Desalination Affected the Arabian Gulf? IDA Journal.

8. Garside, D (2012). Personal communication. TOC Instrument Supplier.

9. Global Water Intelligence (2005) *Water Reuse Markets 2005-2015.* First Edition. June 2005.

10. Howell JA (1995) Sub-critical Flux Operation of Microfiltration. *Journal of Membrane Science.* Volume 107. Issues 1-2. p. 165-171.

11. Judd S (2004) MBRs – An Historical Review and Future Prospects. Cranfield University.

12. Judd S (2011) *Principles and Applications of Membrane Bioreactors for Water and Wastewater Treatment.* 2nd Edition Elsevier Ltd.

13. Leverenz HL, Tchobanoglous G, and Asano, T. (2011). Direct potable reuse: a future imperative. Journal of Water Reuse and Desalination.

14. Melcer H, Tam P, Tse R, Burke P and Hummel S (2004) New Technology for New Plant: Brightwater Membrane Bioreactor Process. WEFTEC.

15. Morgan C, LeBrun LE, van't Oever, R (2006) Innovative Application of Two-Phase Flow Yields Low

16. Qin JJ, Kekre KA, Guihe T, Ooa MH, Wai MN, Lee TC (2006) New option of MBR-RO process for production of NEWater from domestic sewage. Journal of Membrane Science **272**, 70-77.

17. Reid E (2005) Salinity Shocking and Fouling Amelioration in Membrane Bioreactors. EngD Thesis, School of Water Sciences, Cranfield University.

18. Wastewater Engineering (2004) *Wastewater Engineering, Treatment and Reuse.* 4th Edition McGraw Hill. p.845.

ANNEXURES

ANNEXURE A-A

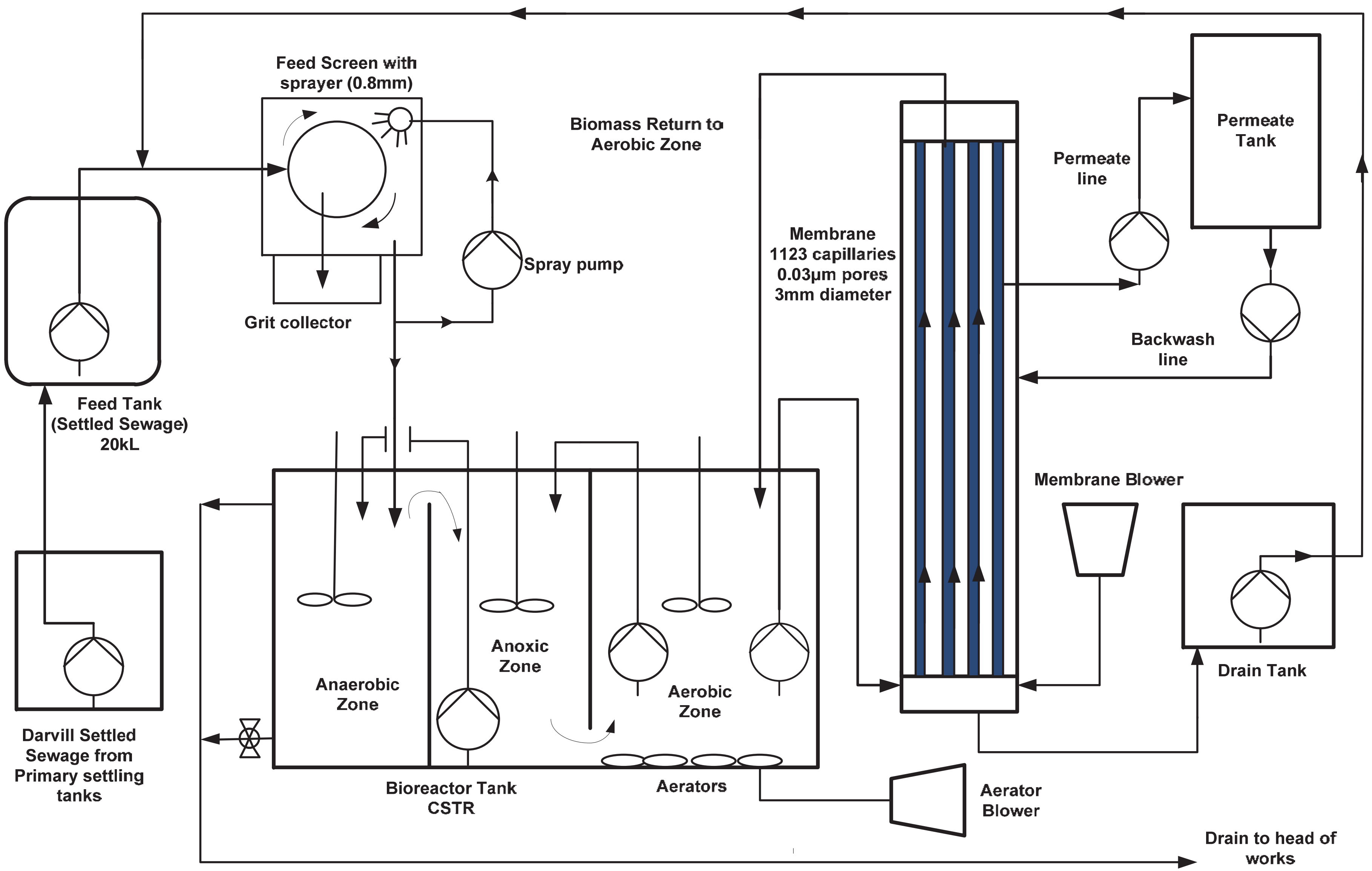
Process Flow Diagrams

a) Norit Demonstration Plant Process Flow Diagram

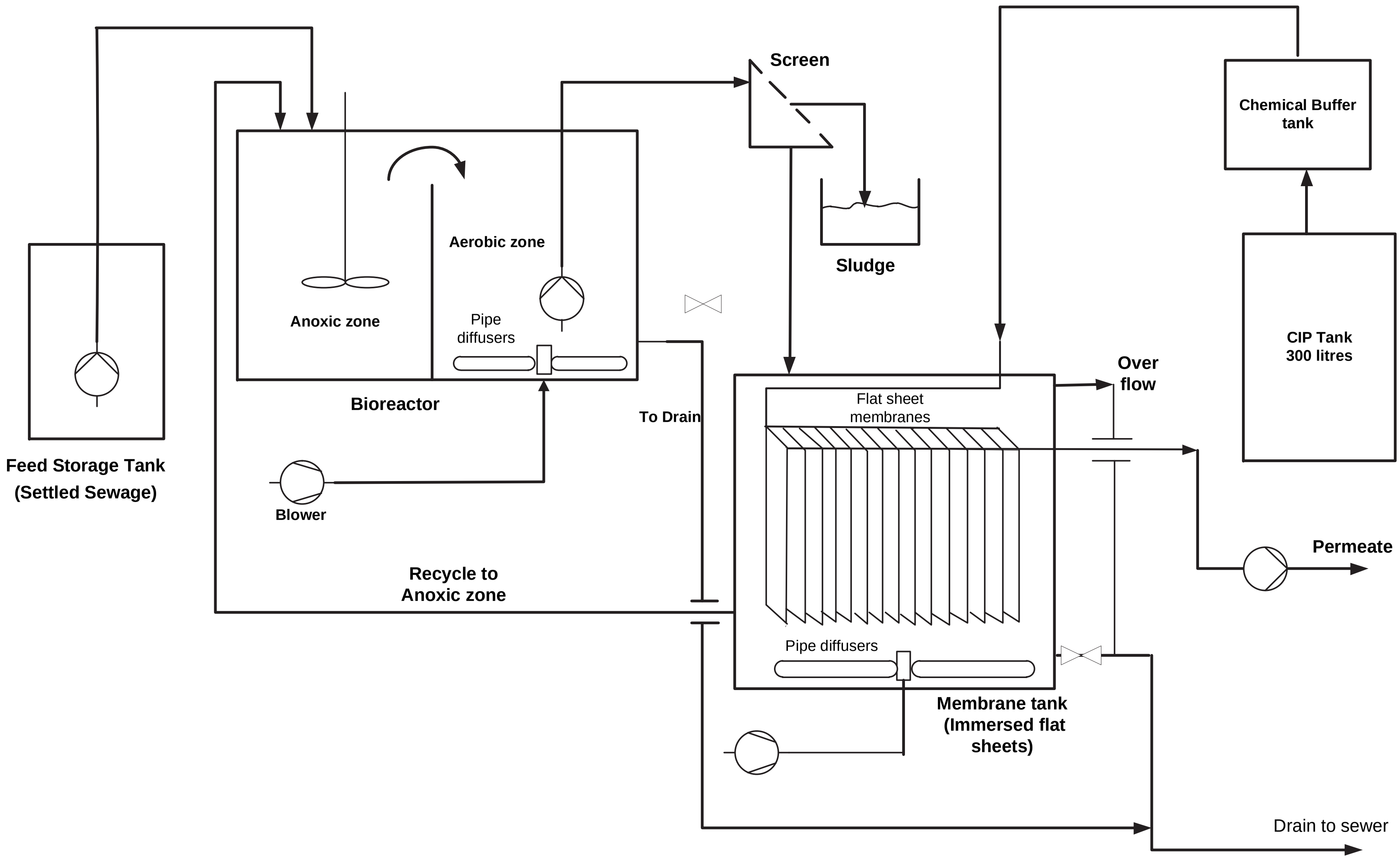
b) Toray Demonstration Plant Process Flow Diagram

c) Pall Corporation Demonstration Plant process Flow Diagram

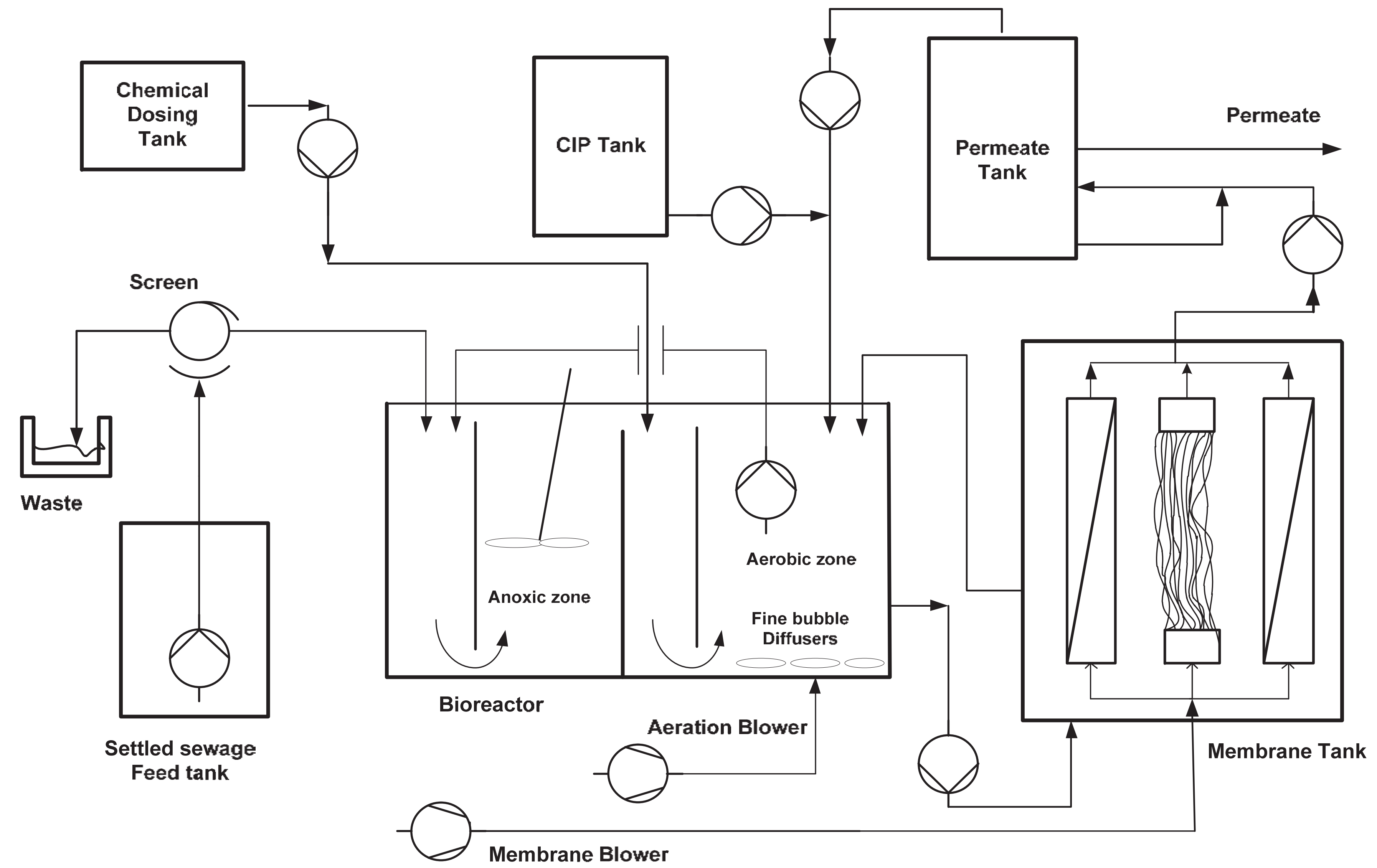
NORIT DEMONSTRATION PLANT PROCESS FLOW DIAGRAM



TORAY MBR DEMONSTRATION PLANT PROCESS FLOW DIAGRAM



PALL CORPORATION DEMONSTRATION PLANT PROCESS FLOW DIAGRAM



ANNEXURE A-B

Chemical Cleaning in Place (CIP) Procedure for Toray and Norit MBR Demonstration Plants

Toray MBR Cleaning Procedure

1. The chemicals used in the cleaning procedure are introduced on the permeate side of the membranes.

2. The trans membrane pressure (TMP) is a guideline for conducting a chemical clean. The TMP is an indicator for membrane fouling.

3. The design TMP for the membranes is 0-(-200 mbar) whilst the operating TMP range is 0-(-180 mbar). When the TMP exceeds -180 mbar, the plant automatically stops running until a clean is done.

4. The two major membrane foulants are organic and inorganic matter and hence a need to use chemicals in the cleaning process. The chemicals must, however, be non-corrosive to the membrane material.

5. For organic fouling, sodium hypochlorite was used on the membranes and for inorganic fouling, citric acid was used.

6. Sodium hypochlorite is a strong oxidiser and disinfectant, which is effective in controlling biological and organic fouling. It acts by oxidising organic foulants within the membrane pores and on the surface.

7. Citric acid is a weak organic acid which is very effective at low pH levels. It is a good chelating agent for calcium, hence a good inorganic foulant removal.

8. For an intensive clean, the following concentrations are used:

    - 4,000 mg/l Sodium Hypochlorite
    - 5,000 mg/l Citric acid

9. For a maintenance clean, the following concentrations are used:

    - 1,500 mg/l Sodium Hypochlorite
    - 2,000 mg/l Citric acid

10. A 300 L chemical mixing tank is used together with a 50 L buffer tank.

11. The mixing tank is filled with potable water and the sodium hypochlorite is added first.

12. The chemical is then dissolved in the water and circulated between the two tanks for 20 minutes for adequate mixing.

13. The tank heater is turned on during the chemical mixing. This aids the temperature of the solution to rise and favours the solubility of the citric acid in the water.

14. The pH and temperature of the solution are then recorded.

15. Membrane filtration is then stopped and cleaning is done whilst the plant is offline.

16. The mixing is then stopped and a feed valve that opens into the permeate line of the membranes is opened.

17. The solution is then gravity fed into the membranes and soaking is carried out for a period of 3 hours.

18. The chemical and buffer tanks are then flushed with potable water to remove all traces of sodium hypochlorite, in preparation for the citric acid.

19. After three hours, the plant is started up for filtration in order to flush out the chemicals. A set of two or more filtrations is required after the soaking. This is also to ensure that when the citric acid is added, it does not come into contact with the sodium hypochlorite as mixing of the two chemicals emits chlorine gas which is hazardous to personnel working in the environment.

20. Prior to stopping the plant for the second chemical clean, readings of the TMP, flow rates, pH, temperature and turbidity are recorded.

21. The chemical tank is filled again with potable water and citric acid is added to the water. A similar procedure for mixing as with sodium hypochlorite, using the buffer tank, is implemented.

22. Membrane filtration is then stopped.

23. The pH and temperature of the solution are recorded prior to the solution being gravity fed into the membranes.

24. Citric acid soaking is done overnight and filtration to flush out the solution is resumed in the morning.

25. Readings are taken on start-up of the filtration sequence, and after a clean. The TMP should show a major reduction as an indication of fouling reduction.

Norit MBR Cleaning Procedure

1. The chemicals used in the cleaning procedure are introduced on the permeate side of the membranes.

2. The trans membrane pressure (TMP) is a guideline for conducting a chemical clean. The TMP is an indicator for membrane fouling.

3. The operating TMP for the membranes is 0-0.5 bar and if the TMP exceeds 0.5 bar, the plant goes into automatic relaxation where filtration automatically stops until a clean is done.

4. The two major membrane foulants are organic and inorganic matter, hence a need to use chemicals in the cleaning process. The chemicals must, however, be non-corrosive to the membrane material.

5. For organic fouling, sodium hypochlorite was used on the membranes and for inorganic fouling, citric acid was used.

6. Sodium hypochlorite is a strong oxidiser and disinfectant, which is effective in controlling biological and organic fouling. It acts by oxidising organic foulants within the membrane pores and on the surface.

7. Citric acid is a weak organic acid which is very effective at low pH levels. It is a good chelating agent for calcium hence a good inorganic foulant removal.

8. For an intensive clean, the following concentrations are used:

    - 500 mg/l Sodium Hypochlorite

    - 2% Citric acid

9. For a maintenance clean, the following concentrations are used:

    - 500 mg/l Sodium Hypochlorite

10. A 500 L permeate tank is used to dissolve the chemicals and permeate is used in the cleaning process.

11. Sodium hypochlorite is added first and left for a short while in order to dissolve.

12. Membrane filtration is then stopped and cleaning is done whilst the plant is offline.

13. The solution is pumped onto the permeate side of the membranes (outside the tubes) using a backwash pump.

14. The sodium hypochlorite soaking is done in three steps:

    1. 30 minutes of soaking and then draining

    2. Another 30 minutes of soaking followed by a drain

    3. Lastly, 1 hour of uninterrupted soaking.

15. After two hours, the solution is drained from the membranes.

16. The permeate tank is flushed with potable water to remove all traces of sodium hypochlorite in preparation for the citric acid.

17. The permeate tank is filled with potable water and the membranes are flushed through backwashing, using 40% of the potable water in the permeate tank.

18. The remaining 60% tank volume is used for addition of citric acid.

19. The citric acid solution is allowed to stand for a while in order to dissolve.

20. A backwash pump is started up to transfer the solution onto the permeate side of the membranes.

21. The citric acid solution in the membranes is left to soak overnight and is drained the following morning.

22. The permeate tank is flushed and filled with potable water to ensure there is available water for backwashing once the plant is started up.

23. The plant is started up with a drain sequence, followed with a backwash sequence and finally a filtration sequence.

24. The membrane TMP is then recorded and should show a considerable reduction after the clean.

ANNEXURE A-C

Photographs

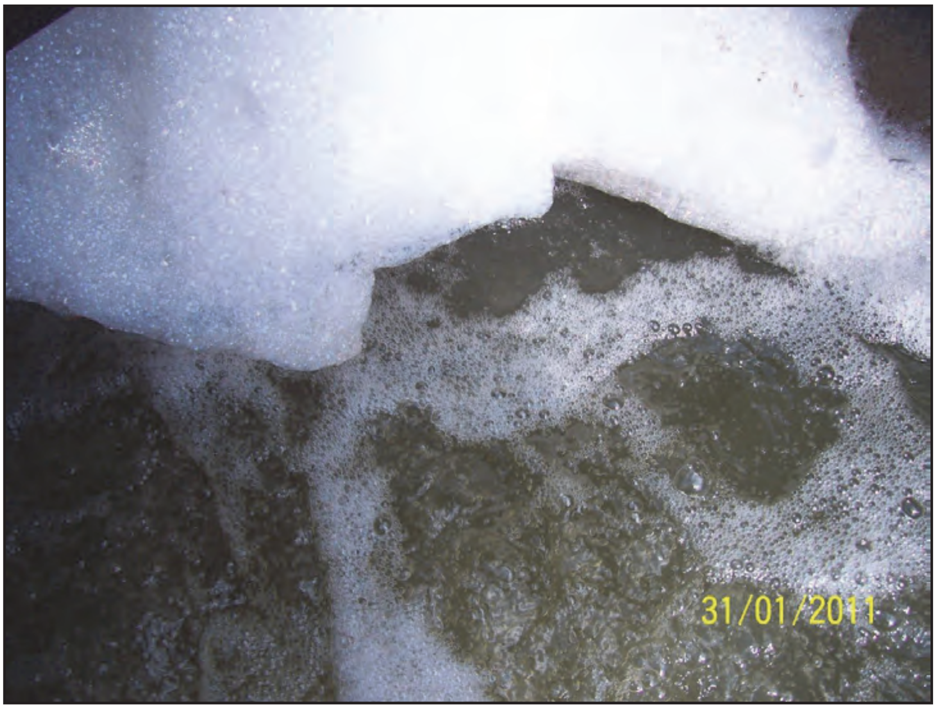


Photo 1: Pollution Incident in Toray Bioreactor. 31st January 2011