



**VICTORIA  
UNIVERSITY**

**A NEW  
SCHOOL OF  
THOUGHT**

**Smart Water Project**

**“Opportunities for Designer Recycled Water” (32M-2030)**

***Milestone 6 Final Report and Dissemination of Results in Accordance  
with Project Plan.***

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**In conjunction with the University of NSW and Arris Pty Ltd**

**October 2008**

## **Executive Summary**

This report is the last and final report for the Round 3 Smart Water Project: “Opportunities for Designer Recycled Water” (32M-2030). It combines and discusses the major results previously presented in the Milestone 2, 4 and 5 reports, and presents, discusses and evaluates the recently performed feasibility and costing study.

The feasibility of producing nutrient rich water for agricultural and horticultural applications using an integrated membrane process consisting of microfiltration (MF), nanofiltration (NF) and reverse osmosis (RO) was investigated. Two types of wastewater were treated using an integrated MF-NF-RO treatment process - municipal wastewater and hydroponics wastewater.

### ***Municipal Wastewater Treatment for Agricultural Irrigation***

Two promising options for the treatment of municipal wastewater that contains approximately 280 mg L<sup>-1</sup> Na, has an electrical conductivity (EC) of approximately 1600 μS cm<sup>-1</sup> and a sodium adsorption ratio (SAR) of approximately 9, were identified:

#### ***Option 1: MF-NF-RO treatment with NF enhancement***

This treatment option utilises a Koch NF element (SR2) with 0.2 g L<sup>-1</sup> polyacrylic acid (PAA) NF enhancement, and promises to yield product water with 92 mg L<sup>-1</sup> Na, EC of 509 μS cm<sup>-1</sup> and a SAR of 3.6, while retaining 36% of original K concentration, 63% of original Mg concentration, 79% of original Ca concentration, 33% of original Total P concentration, and 32% of original Total N concentration and achieving recycled water production rate that is 87% of feed volume.

#### ***Option 2: MF-NF-RO treatment without NF enhancement***

This treatment option utilises a Dow-Filmtec NF element (NF270), and promises to yield product water with 116 mg L<sup>-1</sup> Na, electrical conductivity (EC) of 733 μS cm<sup>-1</sup> and a sodium adsorption ratio (SAR) of 4.0, while retaining 45% of original K concentration, 79% of original Mg concentration, 67% of original Ca concentration, 123% of original Total P concentration, and 27% of original Total N concentration and achieving a recycled water production rate that is 80% of feed volume.

### ***Hydroponics Wastewater Treatment for On-site Reuse in Hydroponics***

Two promising options for the treatment of hydroponics wastewater that contains approximately 130 mg L<sup>-1</sup> Na, and has an EC of approximately 2010 μS cm<sup>-1</sup> were identified:

#### ***Option 1: MF-NF-RO treatment with NF enhancement***

This treatment option utilises a Koch NF element (SR2) with 1.0 g L<sup>-1</sup> polyacrylic acid (PAA) NF enhancement, and promises to yield product water with 42 mg L<sup>-1</sup> Na, EC of 687 μS cm<sup>-1</sup>, while retaining 63% of original K concentration, 64% of original Mg concentration, 81% of original Ca concentration, and 18% of original Total N concentration, and achieving recycled water production rate that is 95% of feed volume. The preparation of nutrient solution using recycled water rather than fresh water was found to result in a small elevation of the expected sodium content and EC. The

sodium content and EC of nutrient solution prepared with fresh water were found to be 53 mg L<sup>-1</sup> and 3000 µS cm<sup>-1</sup> respectively. The calculated expected Na concentration of hydroponic nutrient solution prepared using recycled water from this option was 71 mg L<sup>-1</sup>. This is only 18 mg L<sup>-1</sup> above the sodium content of nutrient solution prepared with fresh water. The salt (NaCl) content of the recycled water is expected to raise the EC of the nutrient solution by approximately 64 uS cm<sup>-1</sup>. This EC increase is unlikely to limit the quantity of nutrient salts that can be added by the grower.

**Option 2: MF-NF-RO treatment without NF enhancement**

This treatment option utilises a Hydranautics NF element (ESNA1), and promises to yield product water with 84 mg L<sup>-1</sup> Na and an EC of 1243 µScm<sup>-1</sup>, while retaining 63% of original K concentration, 86% of original Mg concentration, 90% of original Ca concentration and 33% of original Total N concentration, and achieving a recycled water production rate that is 96% of feed volume. The preparation of nutrient solution using recycled water rather than fresh water was found to result in a small elevation of the expected sodium content and EC. The sodium content and EC of nutrient solution prepared with fresh water were found to be 53 mg L<sup>-1</sup> and 3000 µS cm<sup>-1</sup> respectively. The calculated expected Na concentration of hydroponic nutrient solution prepared using recycled water from this option was 115 mg L<sup>-1</sup>. This is only 62 mg L<sup>-1</sup> above the sodium content of nutrient solution prepared with fresh water. The salt (NaCl) content of the recycled water is expected to raise the EC of the nutrient solution by approximately 237 uS cm<sup>-1</sup>. This EC increase is unlikely to limit the quantity of nutrient salts that can be added by the grower.

**Cost considerations**

The estimated costs associated with the two most promising options for the treatment of municipal wastewater for agricultural irrigation at 360 ML/yr can be compared to those of RO-only treatment in the following table:

		Treatment Option*			
		Units	1	2	3
Costs	Power	\$/yr	41k	48k	34k
	Chemical	\$/yr	158k	22k	13k
	Total Operating	\$/yr	396k	268k	215k
	Capital	\$	1.3M	1.3M	0.82M

\*Treatment Option 1: NF-RO treatment with NF enhancement (Koch SR2 NF element, 0.2 g/L polyacrylic acid). Treatment Option 2: NF-RO treatment without NF enhancement (NF270 NF element). Treatment Option 3: RO-only treatment.

## **Conclusions**

This research has provided evidence that MF-NF-RO treatment of wastewater is a feasible and potentially useful alternative to RO-only treatment that promises to provide more and better quality water for irrigation, and a lower waste brine volume than conventional MF-RO treatment. These advantages, however, come at a cost.

MF-NF-RO treatment using the NF270 element in the absence of PAA addition has 1.6 times the capital cost, 1.7 times the chemical costs and 1.4 times the power cost of RO only treatment, and promises to provide product water with moderate Na (116 mg L<sup>-1</sup> and EC values (733  $\mu\text{S cm}^{-1}$ ), and higher P, Ca, Mg and K content (5.2, 2.7, 3.4, and 2.3 times the RO-only values respectively) and lower waste brine volumes (0.6 times the RO-only values) than RO-only treatment. This option is expected to provide low salinity product water (EC <750  $\mu\text{S cm}^{-1}$ ) from wastewaters with salinities less than approximately 1600  $\mu\text{S cm}^{-1}$ .

Lower Na (80-90 mg L<sup>-1</sup>) and EC values (approx. 500  $\mu\text{S cm}^{-1}$ ), and waste brine volumes (0.4 times the RO-only values) can be achieved with PAA addition (0.2 g L<sup>-1</sup>), but this is at considerably higher chemical costs – 7 times the NF270 option chemical cost and 12 times the RO-only option chemical costs, increasing the annual operating costs from \$268k to \$396k. This option would be expected to be useful for irrigation of low salt tolerance crops such as lettuce, or for the treatment of wastewater with high salinity.

The production of lower brine volumes by NF-RO treatment is a particularly attractive feature that minimises waste brine transport costs, and would facilitate the drying of the brine and use or disposal of dried salts. If, however, the chosen brine management option is to discharge to the environment, this would need to account for the higher salt and toxicant levels in the more concentrated brine. RO only treatment typically produces brine that contains 3 to 4 times the salt and toxicant concentration in the wastewater before treatment, whereas NF-RO treatment promises to produce brine that contains 5 to 6 times the salt and toxicant concentration in the wastewater before treatment.

This report highlights the advantages, disadvantages and potential of MF-NF-RO treatment, and provides data to facilitate the design of membrane desalination processes to meet the water needs of the agricultural and horticultural industry.

## **Acknowledgement**

The authors thank Smart Water Fund and Victoria University Priority Research Areas Fund for providing financial support of this research. The contributions to this research of Dr Daryl Stevens, Professor Greg Leslie, Professor Stephen Gray and Dr Simon Wilson are greatly appreciated.

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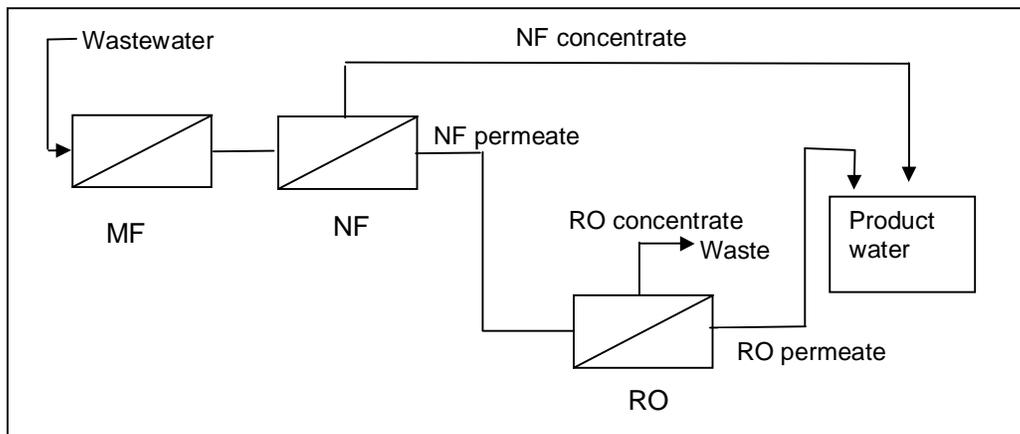
## 1. Introduction

This report is the last and final report for the Round 3 Smart Water Project: “Opportunities for Designer Recycled Water” (32M-2030). It combines and discusses the major results previously presented in the Milestone 2, 4 and 5 reports, and presents, discusses and evaluates the recently performed feasibility and costing study.

The research here described focused on the recycling of two types of wastewater - municipal wastewater and hydroponics wastewater. Both of these wastewaters contain considerable quantities of plant nutrients. The central objective of this research is to retain the nutrients and remove undesirable wastewater constituents such as sodium chloride, thereby producing a fit-for-purpose, higher value, reclaimed water for agricultural and horticultural applications.

The rationale of this treatment process is to include an intermediate nanofiltration (NF) stage in the conventional microfiltration- reverse osmosis (MF-RO) desalination process train. The role of the nanofiltration stage is to retain agriculturally useful ions such as calcium, magnesium and phosphate and allow harmful ions such as sodium to pass through, to be removed from the water by the subsequent reverse osmosis (RO) stage. The retained nutrients (in the NF concentrate stream) are then blended with the treated water from the RO stage (RO permeate stream) to form the nutrient enriched, low salt, product water.

A diagrammatic representation of the proposed MF-NF-RO system is shown in Figure 1.1.



**Figure 1.1:** Proposed MF-NF-RO integrated membrane system

Including an intermediate nanofiltration stage has another major benefit. NF pre-treatment reduces the potential for scaling during RO treatment by lowering the concentration of scale inducing ions in the feedwater to the RO elements, thereby allowing greater RO water recoveries. NF-RO hybrid systems have been used extensively for water softening and desalination (Fritzmann et al., 2007; Ritchie and Bhattacharyya, 2002; Hamed, 2005). Average water recoveries as high as 95% have been reported for the treatment of mining leachate wastewater using integrated NF-RO processes (Raitenbach et al., 2000) \*\*.

The benefits of this process are:

- A product water with a composition that is fit for purpose (useful nutrient ions present, good EC-SAR balance)

- Longer expected RO membrane life due to lower concentrations of scale forming chemicals reaching the RO membranes
- A smaller volume of waste due to the higher RO train water recoveries possible at a low scale forming chemical concentrations
- A more efficient use of limited water resources due to the greater overall water recovery.

### References:

Fritzmann, C., Lowebberg, J., Wintgens, T., and Melin, T., 2007, State-of-the-art of reverse osmosis desalination, *Desalination* 216, 1-76.

Hamed, O. A., 2005, Overview of hybrid desalination systems – current status and future prospects, *Desalination* 186, 207-214.

Raitenbach, R., Linn, T. and Eilers, L., 2000, Treatment of severely contaminated waste water by a combination of RO, high-pressure RO and NF – potential and limits of the process, *J. Membrane Sci.* 174, 231-241.

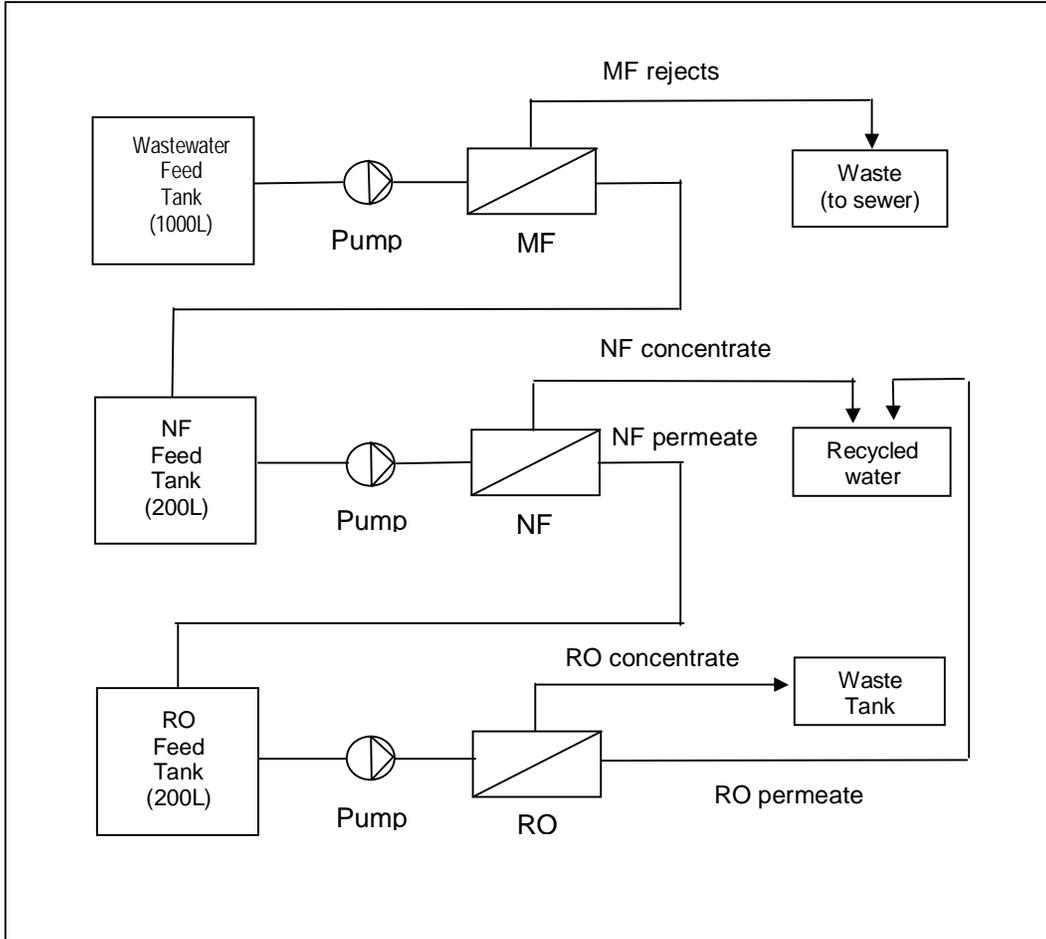
Ritchie, S.M.C. and Bhattacharyya, D., 2002, Membrane-based hybrid process for high water recovery and selective inorganic pollutant separation, *Journal of Hazardous materials* 92, 21-32.

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<sup>\*\*1</sup>Scale inducing ions in the concentrate stream from the later stages of the NF and/or RO treatment process can also be effectively removed by introducing an accelerated seeded precipitation stage, thereby increasing the water recover of the process. A laboratory scale feasibility study of seeded precipitation of calcium from municipal wastewater is shown in Appendix 2. This study was published in March 2008 as part of the communication plan for this project (Sanciolo, P., Zou, L., Gray, S., Leslie, G., Stevens, D., **Accelerated seeded precipitation pretreatment of municipal wastewater to reduce scaling**, *Chemosphere* 72 (2008) 243–249). Another paper titled “**NF and RO membrane treatment of municipal wastewater to produce fit-for-purpose recycled water**” has been submitted to *Water Research journal* in July 2008.

## 2. Pilot Plant Design

A diagrammatic representation of the pilot plant used in these studies is shown in Figure 2.1. The microfiltration (MF) unit is used as a pre-treatment stage to remove suspended particles in the feed water. The MF permeate is used as feed water for the NF membrane element. The NF permeate is, in turn, used as feed water for the RO element. The NF rejects and the RO permeate are blended to produce the recycled water.



**Figure 2.1:** MF-NF-RO plant

Other pilot plant features include: flow transducers fitted to NF and RO feed and concentrate streams; pressure transducers fitted to NF and RO feed and permeate streams; temperature transmitters fitted to NF feed and product water (recycled water) tank; conductivity transmitters fitted at NF concentrate and RO permeate streams; pH meter at product water (recycled water) tank; variable speed drive pumps to NF and RO feed streams; sampling valves at NF and RO feed, concentrate and permeate streams and continuously data logging.

A full process and instrumentation diagram of the pilot plant is shown in Figure 2.2. A layout (top view) of the pilot plant is shown in Figure 2.3.





### **3. Designer Water from Municipal Wastewater**

#### **3.1. Introduction**

Treated effluent from wastewater treatment plants (WTPs), also known as municipal wastewater, can be considered a very valuable resource. It contains considerable quantities of nutrients and it is consistently and reliably produced (330,000 million litres per year), making it an attractive option for irrigation. It also, however, contains medium to high level of salt (NaCl) that prevent it from being directly used for irrigation as it can cause soil salinity and affect crop yield.

This section investigates the feasibility of treating municipal wastewater with an integrated MF-NF-RO membrane treatment process to produce recycled water with useful levels of nutrients and low sodium absorption ratio (SAR) for agricultural irrigation. The rejection behaviour of four different commercially available NF membranes was characterised and then used to predict the expected recycled water composition and water recovery resulting from a multi element NF-RO treatment process.

The feasibility of polymer (PAA) enhancement of NF rejection of Ca and Mg was also investigated. Nanofiltration relies on three mechanisms for the rejection of solutes – Donnan equilibrium, steric hindrance and dielectric exclusion (Baldini and Vezzani, 2003). It is possible to increase the NF rejection of a solute by allowing the solute to form a complex with a high molecular weight organic solute. This enhances the steric hindrance rejection mechanism, allowing higher rejection than would otherwise be the case in the absence of the complexation. This approach has been adopted for the selective removal of strontium and cobalt from wastewater (Hwang et al., 2002) and actinides and lanthanides (Favre-Reguillon et al., 2007) and boron (Gaffen et al., 2006) by nanofiltration, and for heavy metal removal from water (Molinari et al., 2004(a); Molinari et. al., 2004(b); Cojocar and Zakrzewska-Trznadel, 2007; Han et al., 2007) and calcium and magnesium removal from hard water (Tabatabai et al., 1995) by ultrafiltration. The most frequently used polymers are polyethyleneimine and polyacrylic acid (PAA).

#### **3.2. Materials and Experiments**

##### **3.2.1 Wastewater**

The wastewater used in this study was class A treated effluent from a local sewage treatment plant (Western Treatment Plant, Werribee, Melbourne). It was delivered and stored in a 4,000L storage tank and used within approximately one month of delivery. The composition of a sample taken in April 2007 is shown in Table 3.1. The average and standard deviation of the concentration of Na, K Mg, Ca, Total N (nitrate), Total P (phosphate) and total dissolved solids (TDS) of the wastewater used in the NF experiments are shown in Table 3.2. The average electrical conductivity (EC) was  $1654 \mu\text{S cm}^{-1}$  (standard deviation =  $129 \mu\text{S cm}^{-1}$ ). The sodium adsorption ratio (SAR) of the wastewater before treatment was approximately 9.

##### **3.2.2 MF-NF-RO pilot plant**

A diagrammatic representation of the pilot plant used in these studies is shown in Figure 2.1. The microfiltration (MF) unit is used as a pre-treatment stage to remove suspended particles in the feed water. The MF permeate is used as feed water for the NF membrane element. The NF permeate is, in turn, used as feed water for the

RO element. The NF rejects and the RO permeate are blended to produce the recycled water.

**Table 3.1:** Water quality composition of Class A treated effluent (April 2007).

Parameter	Concentration (mg L <sup>-1</sup> )
Alkalinity, as CaCO <sub>3</sub>	150
Fluoride	2.1
Chloride	370
Sulphur, as sulphate	88
Calcium	31
Magnesium	23
Sodium	250
Potassium	25
Iron	< 0.02
Manganese	0.001
Aluminium	0.01
Barium	0.003
Chromium	0.004
Copper	0.014
Nickel	0.013
Lead	0.002
Zinc	0.017
Mercury, as Hg	< 0.0001
Nitrate, as N	9.7
Nitrite, as N	0.005
Ammonia, as N	< 0.1
Phosphate, as P	9.0
Silica, total as SiO <sub>2</sub>	8.7

### 3.2.3 NF membranes

The following commercially available NF and RO elements were used in this study: Koch Membrane Systems, Model 2540 TFC-SR2 N1, nanofiltration element with 31 mil (0.8 mm) feed spacer; Dow Filmtec Membranes, Model NF200-2540, nanofiltration element with 28 mil (0.7mm) feed spacer; Dow Filmtec Membranes, Model NF270-2540, nanofiltration element with 28 mil (0.7 mm) feed spacer; GE Osmonics, Model DK-2540c, nanofiltration element with 47 mil (1.27 mm) spacer; and Dow Filmtec Membranes, Model BWRO-2540, reverse osmosis element with 28 mil (0.7 mm) feed spacer. A summary of the characteristics of the NF membranes is given in Table 3.3.

### 3.2.4 Experimental procedure

The pilot plant was fitted with one of the four nanofiltration membranes and the Dow BWRO-2540 reverse osmosis element. Membrane performance was evaluated, at permeate fluxes between 18 and 24 L m<sup>-2</sup> h<sup>-1</sup>, by analysing the feed, concentrate and permeate streams for Na, K, Mg, Ca, Total N, Total P, TDS and EC. Each run was approximately 30 minutes in duration.

Analysis for Na, K, Mg and Ca was performed using a Varian Atomic Absorption Spectrophotometer. Analysis for Na and K were performed using an Air-acetylene flame. Analysis for Mg and Ca were performed using a nitrous oxide- acetylene flame. Analysis for Total Nitrogen and Total Phosphorus was performed using Hach

Test Analysis kits. Total N analysis was performed using the Persulfate Digestion Method 10072. Total P analysis was performed using the Molybdovanadate, Acid Persulfate Digestion Method 10127. The TDS was determined gravimetrically (Standard Method 2540C, APHA). The EC was determined using a Hanna conductivity meter.

Chemical dosing of the wastewater was performed in the Pilot Plant NF feed tank. Polyacrylic acid (Typical Mw 1,800, Sigma-Aldrich) was used instead of sodium polyacrylate in order to avoid elevation of the sodium content of the wastewater. The pH was adjusted to the native pH (7.8) by addition of KOH (BDH).

**Table 3.2:** Average and standard deviation of concentrations of Na, K, Mg, Ca, Total N, Total P and TDS in WTP wastewater before treatment.

Parameter	Average	Standard deviation
Na	279	19
K	27.8	2.6
Mg	26.5	2.2
Ca	34.7	2.5
N	22.8	4.0
P	23.2	4.6
TDS	1082	88

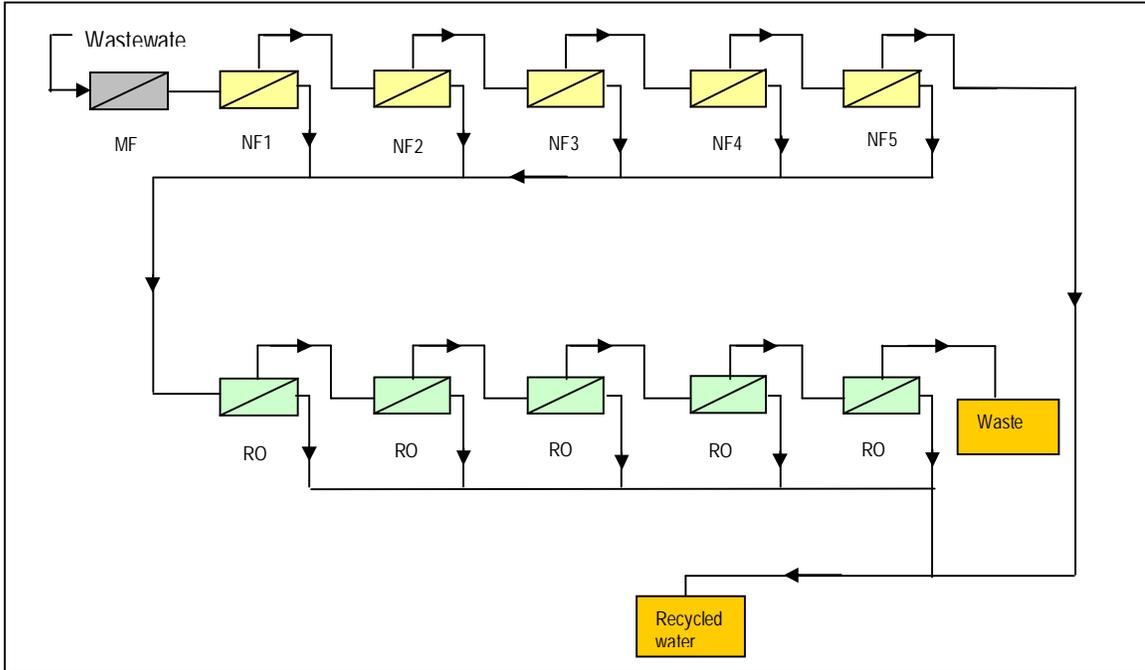
**Table 3.3:** Description, mean pore radius, molecular weight cut off (MWCO) and active surface area of NF membranes

Element	Description	Mean Pore diameter (nm)	MWCO (Da)	Active surface area (m <sup>2</sup> )
SR2	polyamide thin-film composite with a microporous polysulfone supporting layer.[a]	1.28 [a]	300-400 [b]	2.5
NF200	three-layer polysulfone based membrane with a poly Piperazine top layer	0.31 [d]	200-300 [c]	2.6
NF270	three-layer polysulfone based membrane with a poly Piperazine top layer	0.71 [d]	300 [e]	2.6
DK	three-layer thin film polysulfone based membranes with a polyamide top layer [f]	0.42 [f]	200 [f]	1.8

<sup>a</sup>. Nghiem and Hawkes, 2007; <sup>b</sup> Abbas and Hossain, 2006; <sup>c</sup> Curtas-Urbe et al., 2007; <sup>d</sup> Hilal et al., 2005; <sup>e</sup> Lin et al. 2007; <sup>f</sup> Bargeman et al., 2005

### 3.2.5 Modelling of recycled water quality

Modelling of designer water quality was based on a series array configuration of NF and RO elements. The number of NF and RO membrane elements used in the modelling was varied such that the concentration of calcium in the concentrate stream of the last element in the series remained below 100 mg L<sup>-1</sup>. A 5 NF / 5 RO series array is shown in Figure 3.1.



**Figure 3.1:** MF-NF-RO system configuration using 5 NF and 5 RO elements

The following formulae were used to calculate the concentration of the eight chosen water quality parameters in the feed, concentrate and permeate stream of each NF and RO element in the series, and in the recycled water:

$$C_p = C_f (1 - (R / 100))$$

$$C_c = \frac{(C_f V_f - C_p V_p)}{V_c}$$

$$V_p = V_f - V_c$$

$$V_c = V_f (1 - Wr / 100)$$

$$\text{Reverse Osmosis } C_f = \frac{\sum (\text{Nanofiltration } C_p \cdot V_p)}{\sum (\text{Nanofiltration } V_p)}$$

$$\text{Reverse Osmosis } V_f = \sum (\text{Nanofiltration } V_p)$$

$$C_{rw} = \frac{(C_c V_c \text{ of last NF element} + \sum (\text{Reverse Osmosis } C_p V_p))}{(V_c \text{ of last NF element} + \sum (\text{Reverse Osmosis } V_p))}$$

$$SAR = \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}] + [Mg^{2+}]}{2}}}$$

Where:

$C_f$  = concentration of the feed stream (experimentally determined for NF elements and calculated for RO elements)

$C_p$  = concentration of permeate stream

$C_c$  = concentration of concentrate stream

$C_{rw}$  = concentration of recycled water

$V_f$  = volume of the feed stream  
 $V_p$  = volume of permeate stream  
 $V_c$  = volume of concentrate stream

$W_r$  = water recovery (experimentally determined for NF)  
 $R$  = rejection (%)

SAR = sodium adsorption ratio

$[Na^+]$  = concentration of Na in meq  $L^{-1}$  = concentration of Na in  $mg L^{-1} / 23$

$[Mg^{2+}]$  = concentration of Mg in meq  $L^{-1}$  = concentration of Mg in  $mg L^{-1} / 12.2$

$[Ca^{2+}]$  = concentration of Ca in meq  $L^{-1}$  = concentration of Ca in  $mg L^{-1} / 20$

The NF element's solute rejection was determined experimentally for a single stage pass. Calculation of the expected recycled water quality from multistage MF-RO treatment (see Figure 3.1), required making assumptions about the NF rejection of the other stages in the process. For experiments in the absence of PAA, the NF element rejection of each NF stage was assumed to be the same as the experimentally determined single stage pass. For experiments in the presence of PAA, the rejections were increased with each stage in the NF pass due to the expected increase in PAA concentration in the retentate stream, assuming 100% rejection of PAA. The parameter rejection data at various PAA doses shown Table 3.4 were then used to predict the rejection. Based on experimental trials of the RO element with the various NF permeates (results not shown) the RO element's solute rejection for all water quality parameters was set at 98% for all stages in the RO pass.

The number of NF stages was determined by setting a maximum retentate Ca concentration at  $100 mg L^{-1}$ . The  $100 mg L^{-1}$  Ca limit was set in view of previous work with this wastewater (Zach-Maor et al., 2008) which showed that in the absence of antiscalants, scale formation begins to occur in the RO treatment of this wastewater when the Ca concentration exceeds approximately  $100 mg L^{-1}$ . This limit is a conservative one for the NF train in the light of the fact that polyacrylic acid can act as an antiscalant (Darton, 2000).

The NF element water recovery for each NF stage was assumed to be the same as that of the experimentally set single stage pass. For the NF-RO process, the RO element's water recovery was set at 30% for all stages in the RO pass. This was considered to be a safe water recovery in view of the pre-treatment offered by the NF stages.

### 3.3. Results and Discussions

#### 3.3.1 NF rejections behaviour

The rejection results for the four NF membrane elements are shown in Table 3.4.

**Table 3.4:** Rejection (%) behaviour of NF elements, all experiments performed at native pH (7.8) unless otherwise stated. **Note:** pH adjustment increased the starting K levels in the wastewater from approximately 28 mg L<sup>-1</sup> to 114, 232 and 292 mg L<sup>-1</sup>, at 0.2, 0.5 and 0.7 g L<sup>-1</sup> PAA respectively.

NF Element	PAA Dose (g L <sup>-1</sup> )	Permeate flux (L m <sup>-2</sup> h <sup>-1</sup> )	Parameter rejection (%)							
			Na	K	Mg	Ca	Total N	Total P	TDS	EC
SR2	0	18	4.6	5.0	12.0	12.7	6.5	50.3	5.5	3.2
NF200	0	16	24.1	25.5	49.3	47.6	3.8	100.0	27.5	24.5
NF270	0	18	34.1	34.5	71.1	61.4	4.5	100.0	25.1	34.9
DK	0	19	37.3	45.3	97.5	95.0	26.7	100.0	53.6	46.6
SR2	0.2	21	5.1	11.3	31.9	48.0	5.3	7.7	18.3	3.5
SR2	0.5	18	9.6	12.4	66.0	81.3	0.0	2.1	24.7	5.9
SR2	0.7	18	10.9	19.3	84.4	90.9	0.0	3.3	37.0	9.2
SR2 (pH 6)	0.2	21	4.6	4.8	23.1	31.8	0.0	1.7	17.1	1.9

Organic polymer membranes such as the ones used in the current study are negatively charged at near neutral pH conditions. For such membranes, solute rejection is dominated by the electrical repulsion of anions. All things being equal, the greater the charge of an anion, the more it will be repelled and rejected by the NF membrane. The greater negative charge of phosphate is the major determining factor for the much higher rejection (Table 3.4) than nitrate (the size of the ion also plays a role). Low and often negative rejection of nitrate by NF membrane has been documented in literature studies of wastewater (Bollena and Drewes, 2007). In the presence of a more readily rejected ion such as sulphate, nitrate movement through the membrane increases to preserve electrical neutrality across the membrane (Paugam et al., 2004).

When PAA is dissolved in water at near neutral pH, the polyacrylate anion is generated. This ion is not only highly charged, but also very large. The rejection of this ion is very high and influences the fate of other anions. The addition of PAA can be seen to decrease both phosphate and nitrate rejection (Table 3.4). This is consistent with the build up of negative charge on the concentrate side of the membrane, requiring the movement of smaller, more permeable, anions across the membrane to preserve electrical neutrality.

The rejection of anions by the membrane, in turn, requires the concomitant rejection of cations to preserve electrical neutrality across the membrane (Donnan effect). The cations that are rejected to preserve electrical neutrality are those that have the lowest permeability, i.e., the cations with the largest effective radii of hydration. For chloride solutions of sodium and calcium, for example, calcium is rejected more strongly than sodium due to its higher Stokes radius and lower diffusivity (Wang 2005). This is also seen in the data in Table 3.4, where the rejection of monovalent cations ( $\text{Na}^+$ ,  $\text{K}^+$ ) is lower than that of divalent ion ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ). Charge and size effects, however, are not the only determinates of NF membrane performance. In addition to charge and size effects there is dielectric exclusion. This phenomenon is caused by the difference in dielectric constants of the solution and the dielectric constant of the membrane interface, and always causes ion repulsion independently of the sign of ionic charge. Dielectric exclusion is, therefore, greater for divalent ions and multivalent ions (e.g.  $\text{HPO}_4^{2-}$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ) than for monovalent ions (e.g.  $\text{NO}_3^-$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ), (Baldini and Vezzani, 2003).

It is noteworthy that high rejection cannot be correlated with literature pore size data for the membranes. While the poor nutrient ion rejection of the SR2 membrane is consistent with the significantly higher mean pore radius of the SR2 membrane compared to the other membranes (see Table 3.3), the trend in rejection cannot be correlated with the pore size data for the other membranes. The literature mean pore size for the NF 200 is smaller than that of the DK, yet the DK element exhibits greater rejection. Similarly, the NF 270 has a higher mean pore size than the NF200, yet it exhibits greater rejection. Clearly, explanation of the differences between the membranes would require consideration of the balance of the Donnan equilibrium, steric hindrance and dielectric exclusion rejection mechanisms (Baldini and Vezzani, 2003).

The rationale of the proposed NF-RO treatment process is to use nanofiltration (NF) to divert agriculturally useful ions such as calcium, magnesium and phosphate and scale inducing ions (e.g. Ca) to the recycled water, leaving undesirable ions such as sodium to be removed from the NF permeate by the subsequent RO stage (see Figure 2.1). The lower scalant concentration reaching the RO should, in turn, allow the RO to work more efficiently and produce a smaller volume of waste for disposal. The key indicators of suitability of an NF membrane for its use in the proposed process are therefore (a) low Na, TDS and EC rejection, (b) high nutrient ion rejection (K, Mg, Ca, Total N (nitrate) and Total P (phosphate)) rejection and (c) high scalant (Ca) rejection.

#### **3.3.1.1 Na, TDS and EC rejection**

Since the proposed NF-RO process utilises the NF rejects to make up some of the volume of the recycled water (see Figure 2.1), low Na, TDS and EC rejection are required to achieve low recycled water salinity. In the absence of added PAA, the lowest Na, TDS and EC rejection was achieved with the SR2 element (4.6%, 5.5% and 3.2% respectively, Table 3.4).

A qualitative, best-to-worst, ranking of the suitability of the tested NF elements for use in the proposed NF-RO treatment process according to their ability to keep the recycled water salinity low is as follows:

SR2 > SR2PAA > NF200 > NF270 > DK

A more quantitative estimate of how well the tested elements would keep the salinity of the recycled water low is discussed in section 3.3.2.

### 3.3.1.2 Nutrient ion (K, Mg, Ca, nitrate and phosphate) rejection

A qualitative, best-to-worst, ranking of the suitability of the tested NF elements for use in the proposed NF-RO treatment process according to their ability to keep the recycled water nutrient content high is as follows:

DK > NF270 > NF200 > SR2

The SR2 +PAA option would be ranked second best if Ca and Mg rejection alone are deemed to be important. If, however, phosphate rejection is deemed to be important, the SR2+PAA option would be ranked at the worst.

From a practical perspective, it is clear that in the absence of PAA, a compromise must be made between high nutrient ion content of the recycled water and the salinity of the recycled water. The use of the SR2 with low PAA doses, however, allows high nutrient (Ca and Mg) contents to be achieved without raising the salinity. A more quantitative comparison of the SR2+PAA treatment option to the other options will be made in section 3.3.2.

### 3.3.1.3 Scalant Rejection

Calcium can be classified as a nutrient ion, but it also is a major scale inducing ion. It can form low solubility salts such as  $\text{CaCO}_3$ ,  $\text{CaF}_2$ ,  $\text{CaSO}_4$  and  $\text{CaHPO}_4$  on the membrane surface, reducing the production of clean water (permeate flux) and lifetime of the membrane. The removal of Ca from the process stream by NF treatment allows the RO elements to produce more clean water and less waste from every litre of wastewater treated. It also extends the useful lifetime of the RO membrane(s).

The difference in Ca rejection behaviour of the four tested NF membranes has already been discussed (section 3.1.2). A qualitative, best-to-worst, ranking of the suitability of the tested NF elements for use in the proposed NF-RO treatment process according to their ability to achieve high water recovery is as follows:

DK > SR2PAA > NF270 > NF200 > SR2

A more quantitative comparison of the recycled water recovery will be made in section 3.3.2.

## 3.3.2 Calculation of expected MF-NF-RO recycled water quality and overall water recovery

In order to take full advantage of the enrichment function of nanofiltration with respect to nutrients, and the desalination function of the reverse osmosis, it is necessary to run multistage NF-RO configurations. A two-pass configuration consisting of 5 NF stages and 5 RO stages is shown in Figure 3.1. The quality of the recycled water resulting from treatment using such a configuration depends on the NF and RO solute rejection, the number of NF and RO stages and the water recovery of each NF and RO stage.

The calculated expected quality of the recycled water using a multistage NF-RO treatment process is shown in Table 3.5 and Table 3.6. In Table 3.5 the recycled water concentrations are expressed as  $\text{mg L}^{-1}$  and  $\mu\text{S cm}^{-1}$ . The SAR of the recycled water and the water production rate is expressed as percent of the feed wastewater volume. Since these studies were performed on different wastewater samples with varying constituent concentrations (see Table 3.2), the concentrations in Table 3.5 are expressed as a percentage of the untreated wastewater concentration in Table 3.6.

The zero NF rejection (ZNFR) control in Table 3.5 and Table 3.6 represents a situation where the NF elements are doing nothing other than divert a proportion of the water to the recycled water, and a proportion of the water to the RO train. Comparison of the ZNFR control results to the experimental results, thus, shows the individual influence of the NF and RO trains on the water quality.

### 3.3.2.1. Recycled water salinity

The recycled water Na, TDS, EC and SAR values in Table 3.5 are all measures of the recycled water salinity. For irrigation purposes, the general aim of the treatment process is to get the Na, TDS and EC as low as possible while maintaining a favourable EC to SAR balance. The higher the SAR, the higher the EC must be to avoid soil sodicity problems. The plant crop, however, has its own individual sensitivity to EC of the irrigation water. Tomato, for example, has a moderate EC tolerance ( $1300 \mu\text{S cm}^{-1}$  for soils with low leach factor (National Resource Management Ministerial Council, 2006). For an irrigation water with a SAR less than 3, an EC of more than  $700 \mu\text{S cm}^{-1}$  is required in order to make the occurrence of sodicity problems unlikely (National Resource Management Ministerial Council, 2006). The ideal irrigation water EC for tomato irrigation in soils with low leach factor (e.g., light clay) for an irrigation water with a SAR less than 3 is, therefore, between 700 and  $1300 \mu\text{S cm}^{-1}$ . If, however, the SAR of the irrigation water is between 3 and 6, as is the case for the recycled waters in Table 3.5, an EC of more than  $1200 \mu\text{S cm}^{-1}$  is required in order to make the occurrence of sodicity problems unlikely (National Resource Management Ministerial Council, 2006).

The SAR and EC values listed in Table 3.5 would be expected to pose a slight to moderate sodicity hazard. With careful management, these recycled waters would be suitable for the irrigation of a variety of crops – the lower the EC, the greater the variety of crops that could be irrigated with the recycled water.

From a recycled water salinity perspective alone, however, there is little or no benefit in using NF-RO over using RO alone (ZNFR controls) unless PAA addition is employed. Generally, in the absence of added PAA, the proposed NF-RO treatment process reduced the SAR value from approximately 9, before treatment, to 4 or 5. It can be seen in Table 3.5, however, that the bulk of decrease in the recycled water SAR is due to the action of the RO train. The SAR for treatment using the SR2 element gave a SAR value of 4.2 while the SAR for the ZNFR control is 4.3. Only 0.1 units can be attributed to the action of the NF train. The contribution of the NF train for the treatment using the NF200 and NF270 is similarly low - a 0.2 unit difference between the experimental results and their ZNFR controls. Despite the higher Ca and Mg rejection of the NF200 and NF270 membranes, the SAR values are higher than for the SR2, primarily due to the concomitantly higher Na rejection of these membranes (see Table 3.4). The only treatment option where a significantly difference between the experimental results and ZNFR control exists is the DK treatment option. The DK treatment option yields a SAR value that is 1.3 units lower than the ZNFR control. The higher Na rejection of this membrane, however, yields a higher SAR value (5.2) than any of the other membrane options. It is also noteworthy that despite the higher Ca and Mg rejection of the DK element (Table 3.4), the SAR of the recycled water is higher than for the other elements (Table 3.5). This can be attributed to the need to use a lower number of NF elements (6 rather than 10) in order to avoid conditions that are conducive to scale formation in the last element in the NF train, i.e., in order to prevent the Ca concentration in the concentrate streams from exceeding the  $100 \text{ mg L}^{-1}$  scaling limit for this wastewater (Zach-Maor et al. 2008).

**Table 3.5:** Calculated recycled water quality, expressed as mg L<sup>-1</sup> and μS cm<sup>-1</sup>, and production rate, expressed as % of feed volume.

NF Membrane	PAA Conc (g/L)	No of NF elements	No of RO elements	Concentration									SAR	Production rate (% of feed)	
				(mg L <sup>-1</sup> )											
				Na	K	Mg	Ca	N	P	TDS	EC				
SR2	0	10	2	74	8	8	11	7	19	266	439	4.2	56		
ZNFR control		10	2	67	7	6	8	6	6	235	408	4.3	56		
NF200	0	10	4	120	13	18	21	8	40	525	807	4.7	81		
ZNFR control		10	3	92	10	9	12	8	10	384	615	4.9	73		
NF270	0	10	4	116	12	24	22	6	26	384	733	4.0	80		
ZNFR control		10	3	73	7	8	9	6	6	279	456	4.2	72		
DK	0	6	10	170	18	27	36	8	20	719	1012	5.2	98		
ZNFR control		6	2	160	16	16	21	8	11	589	882	6.5	70		
SR2	0.2	5	5	92	41	15	26	6	6	613	509	3.6	87		
ZNFR control		5	3	94	38	8	11	6	6	489	537	5.2	74		
SR2	0.5	4	5	101	94	17	30	6	7	830	711	3.7	88		
ZNFR control		4	4	95	84	9	13	6	7	639	694	5.5	83		
SR2	0.7	4	6	106	119	17	28	7	8	901	775	3.9	92		
ZNFR control		4	3	110	116	9	13	8	8	749	802	5.7	75		
SR2 (pH 6)	0.2	5	5	92	10	16	26	6	6	527	492	3.5	82		
ZNFR control		5	3	89	9	8	11	6	6	400	496	4.9	74		

With PAA addition, the achieved SAR values were found to be lower than the any of the treatment options. The difference between the experimental results and the ZNFR controls was also greater with PAA addition than for without, indicating the advantage of NF-RO treatment over conventions RO treatment, mainly due to the combined effect of low Na rejection and high Ca and Mg rejection in the presence of PAA. The lowest recycled water salinity was achieved at 0.2 g L<sup>-1</sup> PAA (Na: 92 mg L<sup>-1</sup>, TDS: 613 mg L<sup>-1</sup>, EC 509 μS cm<sup>-1</sup>, SAR: 3.6).

**Table 3.6:** Calculated recycled water quality, expressed as **% of original wastewater values**

NF Membrane	PAA Conc (g/L)	No of NF elements	No of RO elements	Concentration (% of original wastewater values)							
				Na	K	Mg	Ca	N	P	TDS	EC
SR2	0	10	2	23	25	27	28	23	63	24	23
ZNFR control		10	2	21	21	21	21	19	20	21	21
NF200	0	10	4	42	44	62	59	31	123	44	43
ZNFR control		10	3	33	34	31	34	31	31	32	32
NF270	0	10	4	45	45	79	67	27	123	39	45
ZNFR control		10	3	28	26	26	27	27	28	28	28
DK	0	6	10	60	64	98	97	53	103	69	65
ZNFR control		6	2	56	57	58	57	53	57	56	56
SR2	0.2	5	5	33	36	63	79	32	33	42	32
ZNFR control		5	3	34	33	33	34	32	33	34	34
SR2	0.5	4	5	38	41	70	85	33	36	47	37
ZNFR control		4	4	36	36	37	37	33	36	36	36
SR2	0.7	4	6	38	41	71	84	35	37	48	38
ZNFR control		4	3	39	40	37	39	40	37	40	40
SR2 (pH 6)	0.2	5	5	35	38	64	79	32	34	45	34
ZNFR control		5	3	34	34	32	33	32	34	34	34

### 3.3.2.2 Recycled water nutrient content

The nutrients measured in this study were K, Mg, Ca, Total N (nitrate) and Total P (phosphate). In the absence of added PAA, the highest retention of nutrients in the recycled water was achieved with the DK membrane. The following percentages of the original water nutrient content were achieved with the DK membrane option – 64% K, 98% Mg, 97% Ca, 53% nitrate, 103% phosphate (Table 3.6). The high salinity of the of water from this treatment option (EC:1012  $\mu\text{S cm}^{-1}$ , SAR:5.2), however, significantly decreases the types of crops that can be irrigated with this water. The NF200 and NF270 treatment options offer lower recycled water nutrient content and salinities. The expected recycled water resulting from the use of the NF 270 element had moderate salinity (116 mg L<sup>-1</sup> Na, 733  $\mu\text{S cm}^{-1}$  EC, 4.0 SAR), good nutrient retention (45% of original K content, 79% of original Mg content, 67% of original Ca content, 123% of original Total P content, and 27% of original Total N content) and high recycled water production rate (80% of feed volume, 20% waste brine volume).

In the presence of added PAA, the highest retention of nutrients in the recycled water was achieved at 0.7 g L<sup>-1</sup>. The following percentages of the original wastewater nutrient content were achieved for this treatment option: 41% K, 71% Mg, 84% Ca, 35% nitrate and 37% phosphate. The salinity of the water produced from this treatment option (EC: 775  $\mu\text{S cm}^{-1}$ , SAR 3.9) is considerably lower than for the NF270 option, allowing application to irrigation of crops with lower salt tolerances. Lower nutrient contents and lower salinities, however, were achieved with the SR2 - PAA options (see Table 3.5 and Table 3.6).

### 3.3.2.3 Recycled water production rate

The recycled water from the proposed NF-RO treatment process consists of a blend of NF concentrate (retentate) and RO permeate (see Figure 2.1). Generally, for this wastewater, the system NF train water recovery was 70 to 80% of the feed volume. Thus, for every 100 L of wastewater, 20 to 30 L of NF concentrate is used to make up part of the total recycled water volume. The remaining 70 to 80 L of wastewater are treated by the RO train. The RO train water recovery is, therefore, a major contributor to the overall recycled water production rate. High scalant ion (Ca) removal by the NF train allows the RO train to run at higher water recoveries, resulting in higher overall recycled water production rates. The higher the NF rejection of Ca (Table 3.4), the higher the number of RO elements that can be used before the onset of scale formation (100 mg L<sup>-1</sup> for this wastewater, Zach-Maor et al., 2008), and the higher the achieved recycled water production rate as percentage of the feed volume (Table 3.5). Essentially, the NF train removes calcium from the system that would otherwise reach the RO train and limit the RO train's water recovery. The highest production rates were achieved with the same treatment options that gave the highest nutrient (Ca, Mg) content – the DK and SR2+0.7 g L<sup>-1</sup> PAA options. These options yielded 98% and 92% of the feed volume respectively. The NF 270 option yielded a production rate of 80% of feed volume.

### 3.3.2.4 Cost and environmental considerations

Due to the small scale of the current experiments, and the number of assumptions necessary to calculate the expected recycled water quality for a full scale, multi stage NF-RO treatment process, a comprehensive cost analysis of the current treatment process is beyond the scope of the current study. The cost related discussion will here be restricted to the relative power consumption, chemical costs and waste management cost considerations for the above NF treatment options. A more detailed costing discussion is provided in Section 5 (p. 57) and Appendix 3 (p.95) of this report.

#### 3.3.2.4.1 Energy consumption considerations

The energy costs associated with the NF treatment process are on top of the RO treatment cost, but may be mitigated by lower RO treatment energy consumption due to lower salt concentration to the RO feed stream, lower RO membrane replacement costs and by the ability to achieve higher water recoveries due to the lower concentration of scaling chemicals in the RO feed stream. Indeed, some researchers have claimed that the integration of NF pre-treatment to RO treatment of sea water (SWRO) can lead to significant improvement in the seawater desalination process by increasing the RO train water recovery to more than 70%. The cost of recycled water from the NF-SWRO plant was 27% lower than conventional SWRO (Hassan et al., 1998).

The NF element energy consumption (in Watts) per litre of permeate (per m<sup>2</sup> of active membrane area per hour) for some SR2-PAA treatment options are compared to the energy consumption in the absence of PAA for the SR2, three other nanofiltration elements (NF200, NF270 and DK), and for one RO element in Table 3.7.

**Table 3.7:** Energy cost associated with NF and RO

NF element	PAA conc. (g L <sup>-1</sup> )	Permeate Flux (L m <sup>-2</sup> h <sup>-1</sup> )	Feed flow rate (L min <sup>-1</sup> )	Pressure (kPa)	Power usage (kW)	Power/Flux (W / L m <sup>-2</sup> h <sup>-1</sup> )
Koch SR2	0	18	3.8	122	0.05	2.8
	0.2	21	3.7	221	0.07	3.3
	0.7	18	3.4	226	0.07	3.9
NF200	0	16	5.0	258	0.08	5.0
NF270	0	18	5.2	315	0.10	5.5
DK	0	19	3.9	1099	0.50	26
BW	0	12	5.0	819	0.35	29

It can be seen that the cost of running the SR2 element in the absence of PAA is approximately one tenth the cost of running the RO element and a half that of running the NF200 element. The NF270 consumes slightly more energy than NF200. The energy consumption of the DK element approaches that of the RO. The trend in these results is consistent with the mean pore radius characteristics of these

membrane elements (See Table 3.2). The SR2 element has the largest mean pore radius, lowest operating pressures and lower running costs. The element DK has the smallest mean pore radius, highest operating pressures and highest running costs. The NF200 and NF270 have intermediate pore size radius, operating pressures and running costs.

Addition of PAA increases the energy requirement to maintain the same permeate flux. This can be seen by comparison of the  $0 \text{ g L}^{-1}$  PAA option with the  $0.7 \text{ g L}^{-1}$  PAA option. To maintain a permeate flux of  $18 \text{ L m}^{-2} \text{ h}^{-1}$  the power to flux ratio increase from 2.8 to 3.9. The energy required to run the RO element is approximately nine times more than that required to run the SR2 elements with  $0.2 \text{ g L}^{-1}$  PAA, and approximately seven times more than that required to run the SR2 with  $0.7 \text{ g L}^{-1}$  PAA.

#### **3.3.2.4.2 Chemical costs considerations**

By lowering the concentration of scaling chemicals reaching the RO train, NF pre-treatment promises to reduce the need for antiscalants and pH reduction. Hassan et al., for example, compared the water production rates of SWRO to NF-SWRO and found that NF-SWRO produced 1.7 times more recycled water without the need for antiscalant addition (Hassan et al., 1998).

At  $0.2 \text{ g L}^{-1}$  and  $0.7 \text{ g L}^{-1}$  PAA dose rate and a bulk supply PAA cost of US \$  $1 \text{ kg}^{-1}$  the cost of PAA addition are approximately US\$  $0.2 \text{ kL}^{-1}$  and US\$  $0.7 \text{ kL}^{-1}$  respectively.

At  $0.2 \text{ g L}^{-1}$  and  $0.7 \text{ g L}^{-1}$  PAA dose rate, the KOH requirement to bring the pH back up to the native wastewater pH was  $0.15 \text{ g L}^{-1}$  and  $0.52 \text{ g L}^{-1}$  respectively. At a KOH cost of US\$  $3.9 \text{ kg}^{-1}$  this equates to US\$  $0.58 \text{ kL}^{-1}$  and US\$  $2.09 \text{ kL}^{-1}$  respectively.

The total cost (PAA and KOH) at  $0.2 \text{ g L}^{-1}$  and  $0.7 \text{ g L}^{-1}$  PAA dose rates are therefore US\$  $0.78 \text{ kL}^{-1}$  and US\$  $2.7 \text{ kL}^{-1}$  respectively. PAA addition in the absence of pH adjustment gives rise to a pH of approximately 6. At this pH, the rejection achieved (Table 3.4) and the calculated recycled water quality (Table 3.5 and Table 3.6) at  $0.2 \text{ g L}^{-1}$  were found to be very close to those at the native pH (pH 7.8), indicating that pH adjustment is not necessary. The cost at  $0.2 \text{ g L}^{-1}$  PAA would, therefore, be US\$  $0.2 \text{ kL}^{-1}$ .

#### **3.3.2.4.3 Waste management considerations**

One of the benefits of the NF pre-treatment is that it removes calcium from the system that would otherwise reach the RO train and limit the RO train's water recovery. This gives rise to high recycled water production rate at high Ca rejection. These very high production rates translate to very small waste volume from the proposed NF-RO treatment process. This is a particularly attractive feature that minimises waste brine transport costs, and would facilitate the drying of the brine and use or disposal of dried salts. If, however, the chosen brine management option is to discharge to the environment, this would need to account for the higher salt and toxicant levels in the more concentrated brine. RO only treatment typically produces brine that 3 to 4 times the salt and toxicant concentration in the wastewater before treatment, whereas NF-RO treatment promises to produce brine that is 5 to 6 times the salt and toxicant concentration in the wastewater before treatment.

#### **3.3.2.4.4 Environmental considerations**

Polyacrylic acids have been safely used in detergents and cleaners for many years. They are extensively removed in sewage treatment (due primarily to sorption onto sewage solids) and have a low toxicity to aquatic and terrestrial organisms (Larson et

al., 1997). Their biodegradability, however, is low for molecular weights above 1000, and only complete for molecular weights considerably less than 500.

The PAA used in the current study had a nominal molecular weight of 1800, essentially rendering it poorly biodegradable. Due to its low toxicity, however, the use of this PAA would not be expected to be problematic. Longer-term use may lead to build up in soil and possible alteration of soil structure. The trial of lower molecular weight, more biodegradable, PAA's as nanofiltration enhancers for Ca and Mg, and the investigation of the effect of PAA on soil structure and crop growth are highlighted as a future research needs.

NF pre-treatment reduces the need for antiscalant addition to the RO train (Hassan et al., 1998). If added, antiscalants remain largely in the concentrate stream and will be a considerable component of the waste brine from the process. From this perspective, NF-RO treatment may be more environmentally friendly than RO only treatment.

### **3.4. Conclusions**

The results presented in Section 3 of this report show that NF-RO treatment can produce recycled water with low sodium absorption ratio (SAR) and useful levels of nutrients for agricultural irrigation. The removal of calcium by the NF pre-treatment in the process also allows the RO to operate at higher water recoveries, resulting in higher recycled water production rates and lower waste brine volumes than is possible with RO-only treatment.

Two favourable treatment options were identified:

(1) The expected recycled water resulting from the NF-RO treatment using the Dow NF 270 element had moderate salinity ( $116 \text{ mg L}^{-1} \text{ Na}$ ,  $733 \text{ }\mu\text{S cm}^{-1} \text{ EC}$ , 4.0 SAR), high nutrient retention (45% of original K content, 79% of original Mg content, 67% of original Ca content, 123% of original Total P content, and 27% of original Total N content) and high recycled water production rate (80% of feed volume, 20% waste brine volume).

(2) The expected recycled water resulting from NF-RO treatment using of the Koch SR2 element with  $0.2 \text{ g L}^{-1}$  PAA addition had lower salinity ( $92 \text{ mg L}^{-1} \text{ Na}$ ,  $509 \text{ }\mu\text{S cm}^{-1} \text{ EC}$ , 3.6 SAR), good nutrient retention (36% of original K content, 63% of original Mg content, 79% of original Ca content, 33% of original Total P content, and 32% of original Total N content) and high recycled water production rate (87% of feed volume, 13% waste brine volume).

Of these two options, the SR2-PAA option would be expected to have lower energy requirement associated with running the NF train (approximately half that for the NF270 option), higher chemical running costs, and lower waste disposal costs.

The results presented in this paper expand the options available for recycling of treated sewage effluent wastewater for agricultural applications.

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## 4. Designer Water from Hydroponic Horticultural Wastewater

### 4.1 Introduction

The nationwide volume of hydroponics wastewater produced has been estimated to be of the order of 38 to 95 GL per year, depending on growing and climatic conditions. There is significant growth potential in the hydroponics / soilless horticulture industry, so this number is likely to rise considerably with growing demand for food as the world population grows. A more detailed assessment of the hydroponic industry in Australia is given in Appendix 1 of this report.

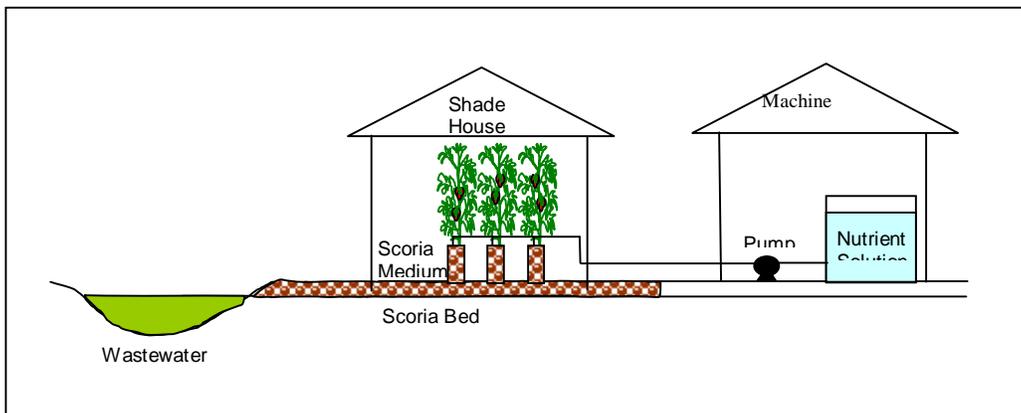
Since hydroponics is a soilless growing process, the use of this wastewater for on-site reuse by the hydroponics grower poses no soil structure problems associated with SAR - EC imbalance. The level of salt (primarily sodium chloride) in the wastewater, however, is a problem since it unnecessarily elevates the electrical conductivity of the water. Each crop has an upper limit of electrical conductivity that is consistent with good yield. Having an elevated water electrical conductivity due to salt (sodium chloride), limits the quantity of nutrient salts that the grower can add to the water while keeping the electrical conductivity below the crop's upper limit for good yield.

This section deals with the application of MF-NF-RO treatment to horticultural wastewater. The feasibility of treating wastewater from a hydroponic tomato farm for on-farm reuse is investigated. The rejection behaviour of two different commercially available NF membranes was characterised and then used to predict the expected recycled water composition and water recovery resulting from a multi element NF-RO treatment process. The feasibility of polymer (PAA) enhancement of NF rejection of Ca and Mg was also investigated.

### 4.2 Characterization of Horticultural Wastewater and Comparison to Nutrient Solution

#### 4.2.1 Introduction

The wastewater used in this study was from a hydroponic tomato grower in Lara, Melbourne. A diagrammatic representation of the farming operation is shown in Figure 4.1.



**Figure 4.1:** Hydroponics tomato farming operation

Three solutions are mixed to produce the nutrient solution:

- Solution A:  $\text{Ca}(\text{NO}_3)_2$ ,  $\text{KNO}_3$
- Solution B:  $\text{MgSO}_4$ ,  $\text{KH}_2\text{PO}_4$ ,  $\text{K}_2\text{SO}_4$ ,  $\text{KCl}$
- Trace elements: Fe Chelate,  $\text{MnSO}_4$ ,  $\text{ZnSO}_4$ ,  $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$ ,  $\text{CuSO}_4$ ,  $\text{Na}_2\text{MoO}_4$

A pump is used to deliver the nutrient solution to the plants via a fine tube inserted in the centre of the scoria (crushed volcanic rock) in the plant pot. The same volcanic rock is used as a bed to allow drainage of excess liquid to the wastewater dam.

Hydroponic systems cannot be run such that all nutrients are removed by the crop as this may limit crop yield. Most hydroponic systems in Australia have a wastewater stream that requires disposal by running to waste. In order to reuse the water for on-site make-up of nutrient solution, unwanted salts that unnecessarily elevate the electrical conductivity of the water must be removed. This allows addition of nutrient to the required level while keeping the electrical conductivity below the crop's upper limit for good yield.

Transpiration of water through plants in the hydroponic system leads to water loss. Since water loss is greater than the total ions (salt) uptake in the hydroponic solution, the wastewater from the hydroponic system is concentrated in salts. The loss of water can range from 50 to 80 percent. This equates to a 2 to 5 times concentration factor of the ions (salts) in solution. However, there is also some ion removal through plant uptake of nutrients. The net result of water loss through transpiration and nutrient uptake by the plants is that the wastewater can be more concentrated than the original nutrient solution with respect to some ions and less concentrated than the nutrient solution with respect to other ions. Since plant nutrient uptake and water loss vary considerably between crops grown, stage of growth, temperature, relative humidity, day length and hydroponic system used, the easiest way to determine which constituents salts increase in concentration and therefore need to be removed in the recycling process is to measure the concentration of constituents in the nutrient solution and compare these to those in the wastewater.

#### **4.2.2 Equipment and procedures**

The wastewater was sampled from the storage dam in mid February. The nutrient solution was sampled from the pump outlet in early March.

Two litre quantities of the two samples were refrigerated within one hour of collection and sent for analysis (EcoWise Environmental Analytical Services) within one day of collection.

#### **4.2.3 Results and Discussion**

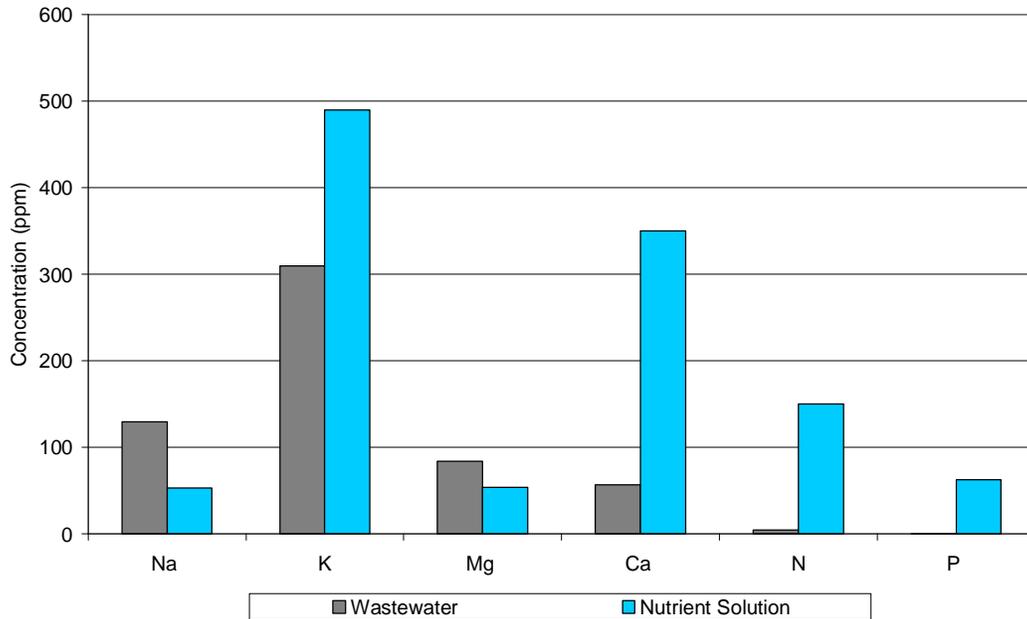
The full chemical composition of the wastewater and nutrient solutions is shown in Table 4.1. A comparison of the Na, K, Mg, Ca, N and P content two waters is shown in Figure 4.2.

**Table 4.1:** Comparison of chemical characteristics of horticultural wastewater and nutrient solution, EC of wastewater = 2013  $\mu\text{S cm}^{-1}$ , EC of Nutrient solution = 2980  $\mu\text{S cm}^{-1}$

	<b>Horticultural Wastewater</b>	<b>Horticultural Nutrient Solution</b>
Alkalinity, as CaCO <sub>3</sub>	160	25
Fluoride, as F	0.66	0.1
Chloride, as Cl	380	230
Sulphur, as SO <sub>4</sub>	460	360
Calcium, as Ca	57	350
Magnesium, as Mg	84	54
Sodium, as Na	130	53
Potassium, as K 1	310	490
Iron, as Fe	0.13	1.6
Manganese, as Mn	0.016	0.58
Aluminium as Al	0.07	<0.1
Barium, as Ba	0.089	0.03
Chromium, as Cr	<0.001	<0.01
Copper, as Cu	0.005	0.06
Nickel, as Ni	0.073	<0.01
Lead, as Pb	<0.001	<0.05
Zinc, as Zn	0.007	0.32
Mercury, as Hg	<0.0001	<0.1
Nitrate, as N	5.0	150
Nitrite as N	0.35	0.03
Ammonia, as N	0.1	16
Phosphate, reactive as P (HL)	0.52	63
Silica, total as SiO <sub>2</sub>	0.9	2.9

The lower concentration of K, Ca, N and P in the wastewater indicates that the tomato plants uptake of these nutrients outweighs the water loss due to evaporation and transpiration. The concentrations of Na and Mg in the wastewater is higher than in the nutrient solution, suggesting that the plant uptake of these components was low and that their concentration increases above that of the nutrient solution by plant transpiration, evaporation in the storage dam and/or, for sodium, by leaching from the surrounding soil or scoria bed.

The expected wastewater concentration of N and P is expected to be low due to the high demand for these nutrients by actively growing and fruiting tomato plants (National Resource Management Ministerial Council 2006). The crop demand for Mg and Ca would be expected to be in higher demand during active stem and leaf growth stages. K would be expected to be in high demand during the flowering and fruit growth stage (National Resource Management Ministerial Council 2006). The expected concentration of K, Mg and Ca would therefore be expected to exhibit considerable seasonal variation.



**Figure 4.2:** Comparison of Na, K, Mg, Ca, N and P content of wastewater and nutrient solutions

#### 4.2.4 Conclusions - Characterization of Horticultural Wastewater and Comparison to Nutrient Solution

The tomato plants crop takes up K, Ca, N and P from the nutrient solution. These nutrients need to be retained by the treatment process and replenished by the farmer before reuse.

The concentrations of Na and Mg in the wastewater is higher than in the nutrient solution, suggesting that the plant uptake of these components is low and that their concentration increases above that of the nutrient solution by evaporation.

Sodium needs to be removed by the treatment process.

### **4.3 Testing of Rejection Behaviour of Koch SR2 and Hydranautics ESNA1 NF Membrane Elements**

#### **4.3.1 Introduction**

The role of the NF element in the proposed MF-NF-RO treatment system is to divert nutrient ions to the product water and allow Na to pass through the membrane to be removed by the RO elements. It is, therefore, important that the NF element used in the proposed process exhibit low Na rejection and a high nutrient ion rejection. Our studies with WTP wastewater have shown that the Koch SR2 element with PAA Ca and Mg NF rejection enhancement can achieve these rejection characteristics.

In the current study, the rejection behaviour exhibited with the Koch SR2 NF element during filtration of horticultural wastewater is characterised. This rejection behaviour is compared to that of another, previously untried, NF element – Hydranautics ESNA1. The effect of addition of various quantities of PAA is tested for both membrane elements.

The effect of flux on the rejection behaviour exhibited by the Hydranautics ESNA1 membrane element (in the absence of added PAA) is also investigated in the current study. The effect of flux on the rejection behaviour exhibited by the Koch SR2 membrane element has previously been studied (see Milestone 4 report) and will not be investigated in the current study.

#### **4.3.2 Equipment and Procedures**

Membrane performance was evaluated at various feed flow rates and permeate fluxes by analysing the feed, concentrate and permeate streams for Na, K, Mg, Ca, Total N, Total P, TDS and EC. Each run was approximately 30 minutes in duration.

##### *Pilot plant*

A diagrammatic representation of the pilot plant used in these studies is shown in Figure 2.1. The microfiltration (MF) unit is used as a pre-treatment stage to remove suspended particles in the feed water. The MF permeate is used as feed water for the NF membrane element. The NF permeate is, in turn, used as feed water for the RO element. The NF rejects and the RO permeate are blended to produce the recycled water.

##### *NF Membranes*

The following commercially available NF and RO elements were used in this study:

- Koch Membrane Systems, Model 2540 TFC-SR2 N1, nanofiltration element
- Hydranautics Hydranautics, Model ESNA12540, nanofiltration element

The pilot plant was fitted with one of the four nanofiltration membranes and the Dow BWRO-2540 reverse osmosis element.

##### *Wastewater Pre-treatment*

For experiments requiring wastewater pre-treatment, chemical dosing of the wastewater was performed in the Pilot Plant NF feed tank. 100L of MF treated wastewater with various quantities of polyacrylic acid (typical Mw 1800, Sigma-Aldrich). The polyacrylic acid was pre-dissolved in approximately 800 mL of MF

treated wastewater and the pH was adjusted to the native pH (~8) with concentrated KOH.

#### *Wastewater*

The wastewater used in this study was sourced from a hydroponics tomato grower in Lara, Melbourne. It was delivered and stored in a 4,000L storage tank and used within approximately one month of delivery.

#### *Analyses*

Analysis for Na, K, Mg and Ca was performed using a Varian Atomic Absorption Spectrophotometer. Analysis for Na and K were performed using an Air-acetylene flame. Analysis for Mg and Ca were performed using a nitrous oxide- acetylene flame.

Analysis for Total N and Total P was performed using Hach Test Analysis kits. Total N analysis was performed using the Persulfate Digestion Method 10072. Total P analysis was performed using the Molybdovanadate, Acid Persulfate Digestion Method 10127.

The TDS was determined gravimetrically (Standard Method 2540C, APHA).

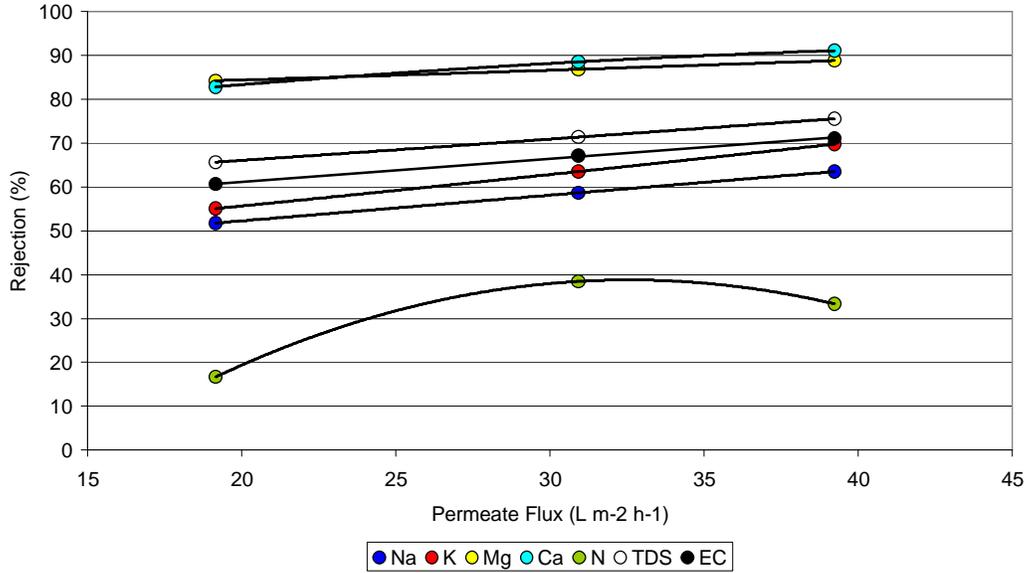
The EC was determined using a Hanna conductivity meter.

### 4.3.3 Results and Discussion

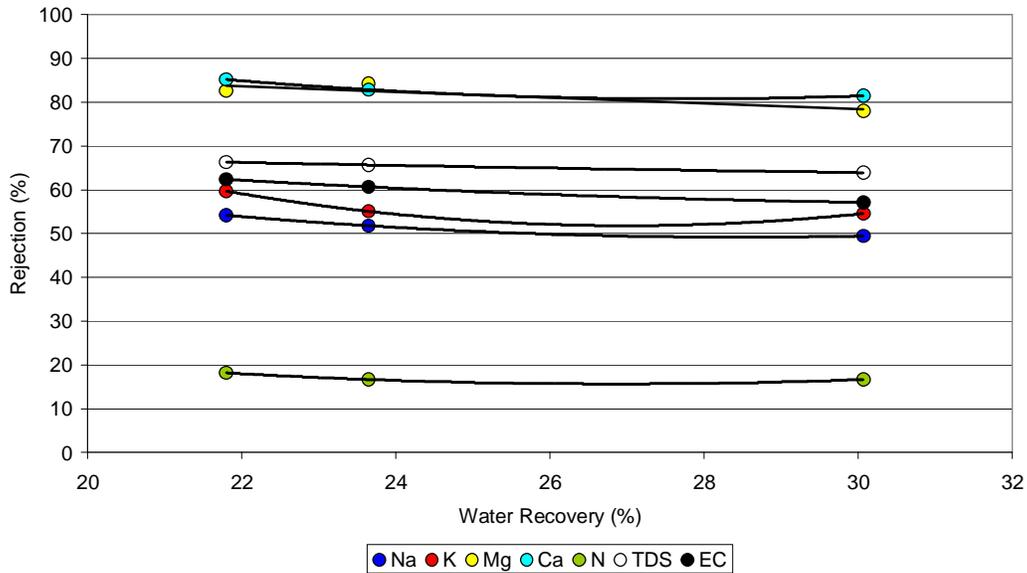
#### 4.3.3.1 Hydranautics ESNA1 NF Element

##### *Effect of permeate flux and water recovery*

The effect of variation in the permeate flux and water recovery on the rejection of the key wastewater parameters by the ESNA element is shown in Figures 4.3 and 4.4 respectively.



**Figure 4.3:** Effect of permeate flux, ESNA1 element, at 22-25% water recovery

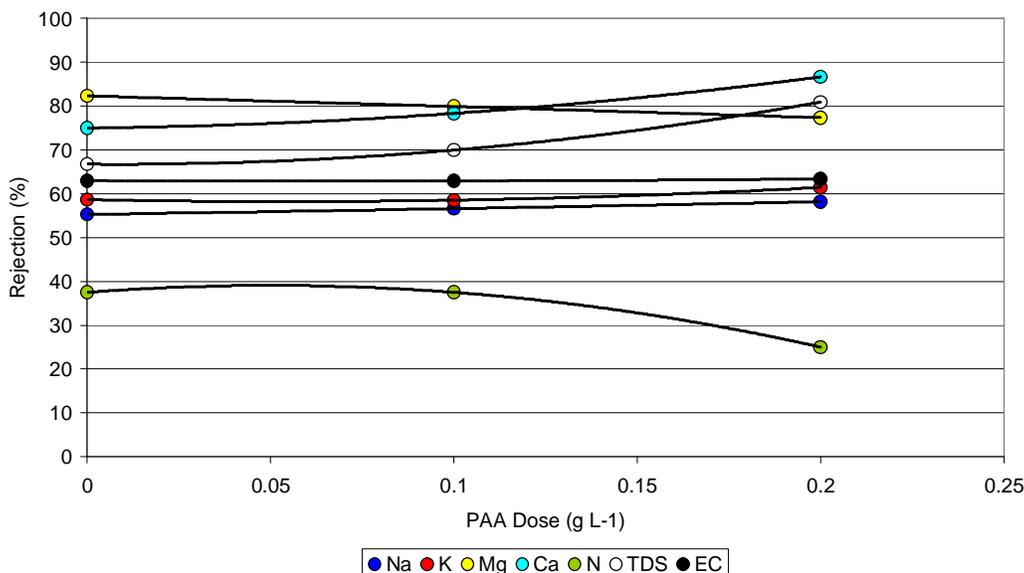


**Figure 4.4:** Effect of water recovery, ESNA1 element, at 19-22 L m<sup>-2</sup> h<sup>-1</sup> flux

Generally, it can be seen that the ESNA element exhibits high calcium and sodium rejection. Ion rejection can be seen to increase mildly with increasing permeate flux (Figure 4.3). A water recovery increase, however, mildly decreases rejection (Figure 4.4). The lowest Na rejection would, therefore, be expected at low flux, high element water recovery conditions. The expected product water quality after MF-NF-RO treatment with the ESNA1 element will be modelled in Section 4.4 (p.39) of this report.

### Effect of PAA addition

PAA addition has, in past experiments, only been adopted with the Koch SR2 element. The SR2 element exhibits low Ca and Mg rejection and is, therefore, an obvious candidate for polyelectrolyte enhancement of Ca and Mg rejection. This study investigates the feasibility of enhancement of Ca and Mg rejection by the ESNA element via polyacrylic acid addition. The rejection results are presented in Figure 4.5.



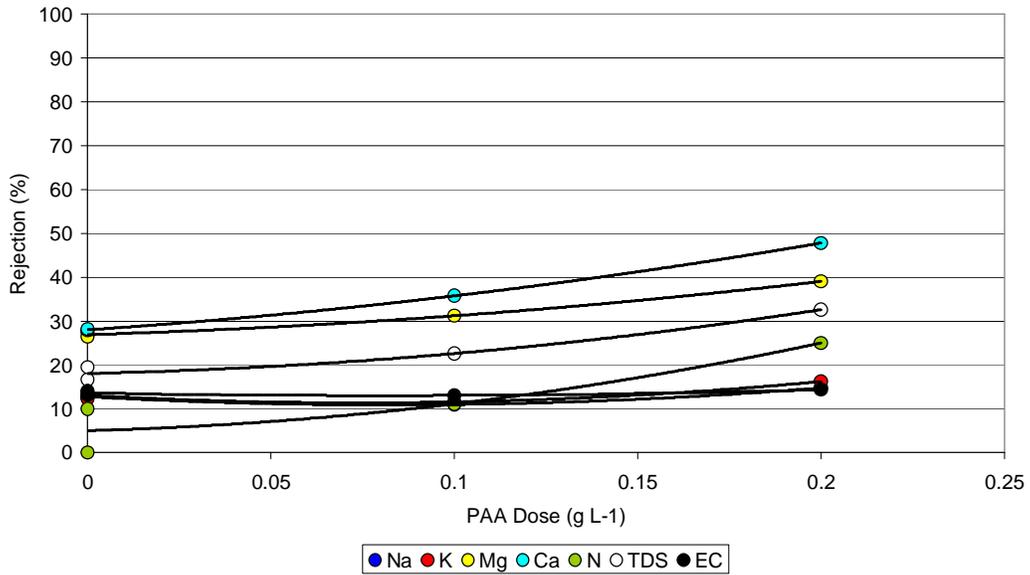
**Figure 4.5:** Effect of PAA dose, Hydranautics ESNA1 element at various PAA doses, 20 L m<sup>-2</sup> h<sup>-1</sup> flux, 25% water recovery

It can be seen that a 0.2 g L<sup>-1</sup> addition of PAA increase the Ca rejection from 75% to 86%, leaving the Na rejection largely unaltered. Oddly, the Mg rejection is decreased mildly by PAA addition. This has not been observed with previous PAA studies with the Koch SR2 element. PAA addition also decreases the nitrogen rejection. This is consistent with an increased permeation of nitrate anion with the increase in concentration of anionic polymer on the concentrate side of the membrane to preserve electrical neutrality across the membrane.

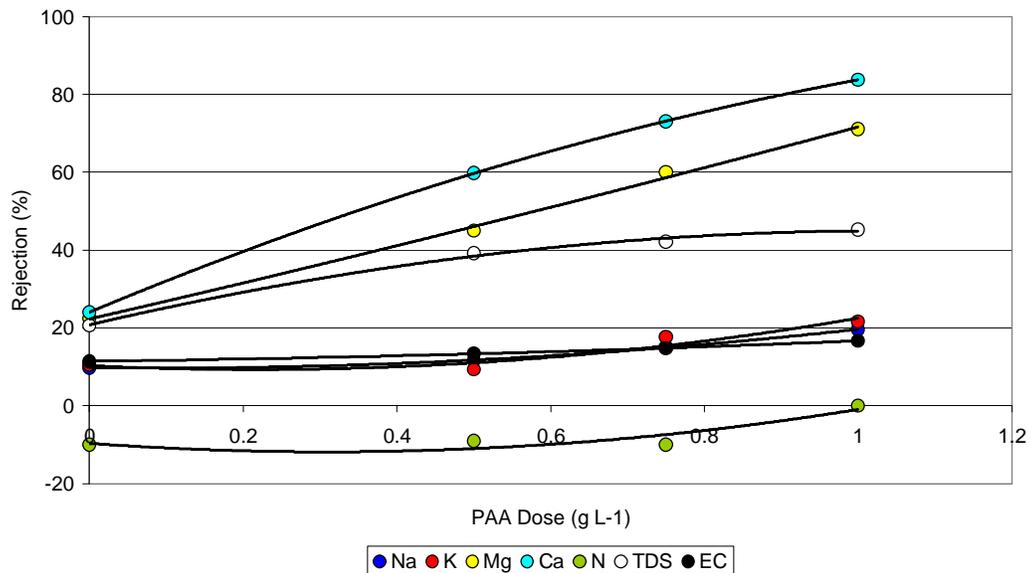
The expected product water quality after MF-NF-RO treatment with the ESNA1 element in the presence of PAA will be modelled in Section 4.4 (p.39) of this report.

### 4.3.3.2 Koch SR2 membrane Element

The rejection behaviour of the Koch SR2 element in the absence and in the presence of various quantities of polyacrylic acid is shown in Figure 4.6 and Figure 4.7.



**Figure 4.6:** Effect of PAA dose, Koch SR2 element, 25% water recovery, 20 L m<sup>-2</sup> h<sup>-1</sup> flux



**Figure 4.7:** Effect of PAA dose, 25% water recovery, 20 L m<sup>-2</sup> h<sup>-1</sup> flux

Figure 4.6 shows the effect of addition of small doses of PAA. Figure 4.7 shows the effect of addition of larger doses of PAA. The two sets of data are presented separately as the experiments were performed on two different wastewater samples.

Comparison of Figure 4.6 with Figure 4.5 (both experiments were performed on the same wastewater sample) shows that, in the absence of added PAA, the ESNA has considerably higher rejection of all the measured parameters than the Koch SR2 element.

Comparison of Figure 4.6 with Figure 4.5 also shows that the effect of PAA addition is more pronounced for the Koch SR2 element than for the Hydranautics ESNA element. For the Koch SR2 element, a  $0.2 \text{ g L}^{-1}$  dose of PAA increases the Ca rejection from 28% to 48%. For the ESNA element, the same dose of PAA increased the rejection from 75% to 87%

The effect of PAA addition was found to be less pronounced for horticultural wastewater than for the WTP water. For horticultural wastewater, the addition of  $1.0 \text{ g L}^{-1}$  PAA was found to increase Ca rejection from 24% to 84% (Fig.4.9). For the WTP wastewater a  $0.7 \text{ g L}^{-1}$  dose of PAA was found to increase Ca rejection from 13% to 91% (Table 3.4). The higher PAA demand by the horticultural wastewater is consistent with the higher Ca concentration in the horticultural wastewater. The horticultural wastewater contains approximately  $80 \text{ mg L}^{-1}$  Ca whereas the WTP wastewater contained approximately  $40 \text{ mg L}^{-1}$  Ca.

#### **4.3.4. Summary and Conclusions - Testing of Rejection Behaviour of Koch SR2 and Hydranautics ESNA1 NF Membrane Elements**

PAA addition makes little or no difference to the rejection achieved with the ESNA element.

The lowest Na rejection achieved with the ESNA element was 52% at  $19 \text{ Lm}^{-2}\text{h}^{-1}$  flux and a 24% water recovery. The Ca retention under these conditions was 82%.

The highest Ca rejection with the ESNA element was 91% at  $39 \text{ Lm}^{-2} \text{ h}^{-1}$  flux and a 24% water recovery. The Na rejection under these conditions was 63%

The lowest Na rejection obtained with the SR2 element was 10-13% The Ca rejection under these conditions was 21-28%.

The highest Ca rejection with the SR2 element was 83% at  $1.0 \text{ g L}^{-1}$  PAA. The Na rejection under these conditions was 20%.

The expected product water quality after NF-RO treatment with the ESNA or SR2 element will be modelled in Section 4.4 (p 39) of this report.

## 4.4 Scaling properties of wastewater and Modelling of Product Water Properties

### 4.4.1 Introduction

In Figure 1.1, the NF and RO components of the proposed MF-NF-RO are represented as single elements for simplicity. In order to achieve the required enrichment by the NF elements, dilution by the RO elements and the required system water recoveries, banks of NF and RO elements may be required. A more detailed representation of one of the possible configurations of the proposed MF-NF-RO system is shown in Figure 3.1 (p. 14).

Although 5 NF elements and 5 RO elements are shown in Figure 3.1, the number of elements (stages) required depends on the feed water quality, the element's rejection characteristics, the operating conditions and the required system water recovery. With each additional NF or RO element, the concentrate stream becomes more and more concentrated. Scaling will occur if the concentration of certain ions (e.g.  $\text{Ca}^{2+}$ ,  $\text{CO}_3^{2-}$ ) becomes too high, so the number of NF or RO elements must be limited to the number that will not be conducive to scaling in the last element in the series.

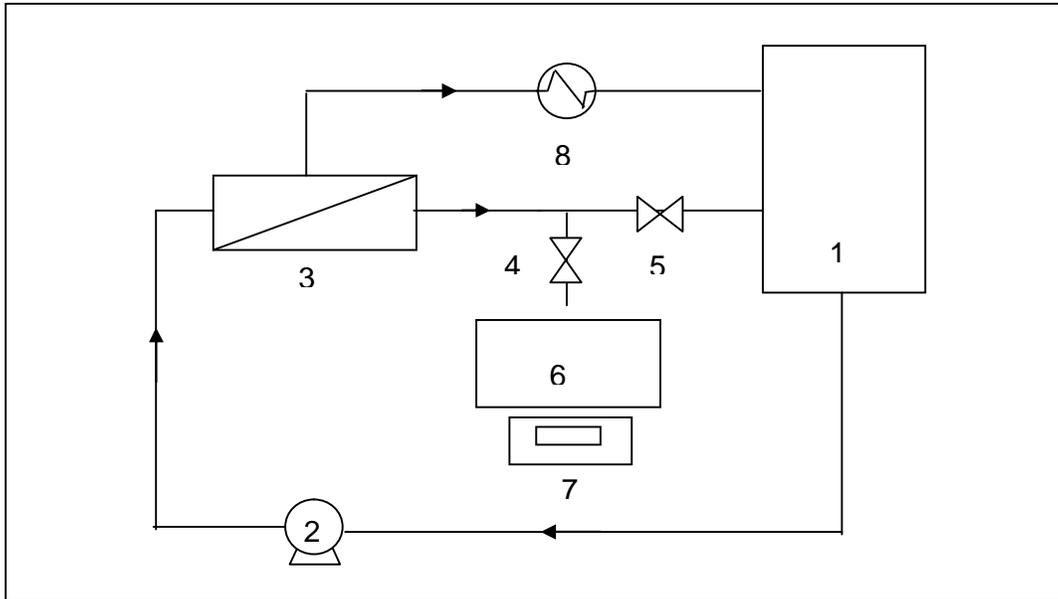
For past modelling of WTP wastewater, the optimum number of NF and RO elements was determined by, firstly, inspecting of the concentrate stream data in a preliminary modelling run using 10 NF and 10 RO elements. The number of NF and RO was decreased until calcium concentration in the concentrate of the last NF or RO element was below  $100 \text{ mg L}^{-1}$ . This concentration was used on the basis of a previous study with this wastewater, which indicated scaling takes place at concentrations greater than approximately  $100 \text{ mg L}^{-1}$  (Zach-Maor et al 2008).

The current study investigates the scaling properties of horticultural wastewater. The ultimate aim of this study is to find the approximate Ca concentration at which scaling is expected to occur in horticultural wastewater. This concentration is then used in the modelling of the expected product water from the proposed MF-NF-RO system using the experimentally determined NF rejection data presented in Section 4.4.3.2 (p.45) of this report.

## 4.4.2 Equipment and Procedures

### 4.4.2.1 Equipment:

The equipment used in the scaling studies is shown in Figure 4.8.



**Figure 4.8:** Diagrammatic representation of equipment used to test the scaling properties of the horticultural wastewater. 1: Wastewater reservoir (90L); 2: high pressure pump; 3: filtration element (NF: Koch SR2 2540 or RO: Dow BWRO 2540); 4,5: valves; 6: permeate reservoir; 7: balance; 8: heat exchanger.

### 4.4.2.2 Run conditions:

The following run conditions were used in the scaling studies:

#### RO Scaling study

- Feed flow rate: 200 L/h
- Permeate flow rate: 60 L/h
- Volume of wastewater: 90 L
- Feed pressure: 1080 kPa
- Temperature range: 21 – 23 °C

#### NF Scaling study

- Feed flow rate: 200 L/h
- Permeate flow rate: 60 L/h
- Volume of wastewater: 90 L
- Feed pressure: 300 kPa
- Temperature range: 17 - 18 °C

### 4.4.2.3 Procedures

#### Scaling experiments

For the SR2 scaling study, the reservoir (Figure 4.8) was filled with 90 L of fresh MF treated horticultural wastewater and then dosed with 140 g of  $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$  (pre-dissolved in MF permeate). The equipment was run for 60 minutes in total recirculation mode prior to dosing with 90 g of PAA (pre-dissolved in MF permeate and adjusted to pH 8.0 with KOH).

For the RO scaling study, the reservoir was filled with 90 L of fresh MF treated horticultural wastewater and then dosed with antiscalant (Flocon 135) at the rate of  $1.5 \text{ mg L}^{-1}$ . The equipment was run for 60 minutes in total recirculation mode (i.e. both permeate and concentrate returned to the wastewater reservoir, see Figure 4.9) prior to commencement of scaling experiment.

At the end of the 60 minute equilibration period, the permeate stream was diverted to the permeate reservoir. The permeate and concentrate streams were sampled for analysis every 5 minutes. The permeate flow rate was determined gravimetrically. The samples were analysed by AAS as previously described, see p 10).

The expected concentrate calcium concentration in the absence of scaling at any time point was calculated by subtracting the total quantity (mg) of Ca lost in the permeate up to that time point from the starting quantity of Ca, and then dividing by the volume of concentrate:

i.e.

$$\text{Concentrate } [\text{Ca}]_t = \frac{(\text{Concentrate } [\text{Ca}]_{\text{start}} \times \text{Vol.}_{\text{start}}) - \sum (\text{Permeate } [\text{Ca}] \times \text{Vol.})}{\text{Concentrate Vol.}_t}$$

#### Modelling of product water qualities

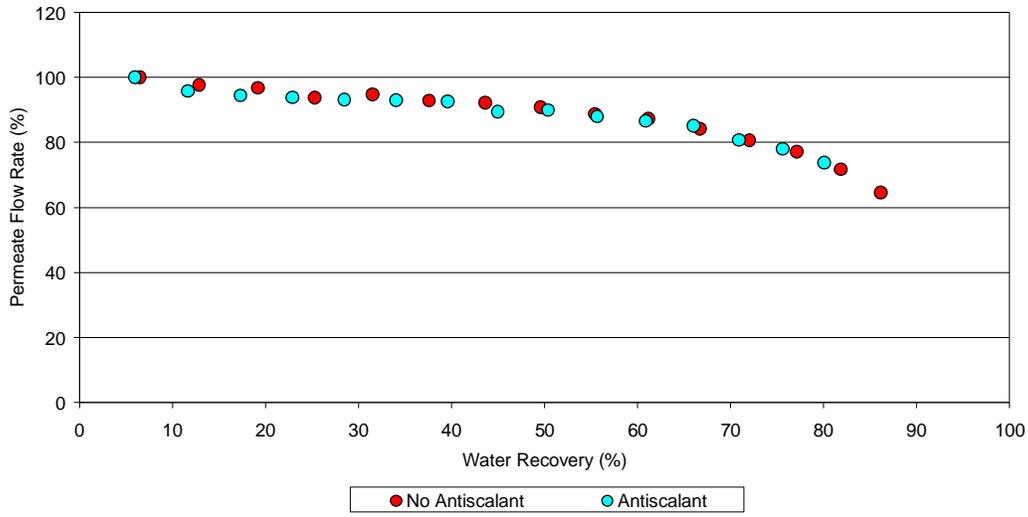
The modelling equations, feature and assumptions are as previously outlined in Section 3.2.5 (p.14) of this report. The concentrate calcium upper limit used to determine the number of NF and RO elements were  $500 \text{ mg L}^{-1}$  for the NF train and  $400 \text{ mg L}^{-1}$  for the RO train (see results of scaling studies, Section 4.4.3.1, pp. 42-44).

### 4.4.3 Results and Discussion

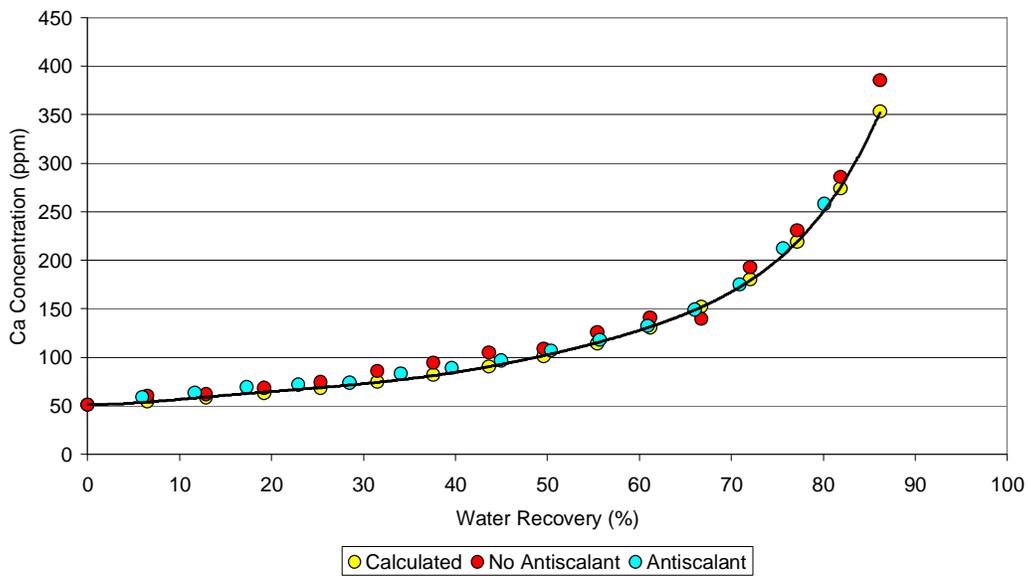
#### 4.4.3.1. Scaling study

##### RO scaling test

The influence of water recovery on the RO permeate flux in the presence and in the absence of antiscalant ( $1.5 \text{ mg L}^{-1}$  Flocon 135) is shown in Figure 4.9. The calcium concentration of the water in the wastewater reservoir during the course of the experiment is shown in Figure 4.10.



**Figure 4.9:** Permeate flux as function of water recovery, RO element, with and without antiscalant ( $1.5 \text{ mg L}^{-1}$  Flocon 135), initial flux  $\sim 60 \text{ L h}^{-1}$ .



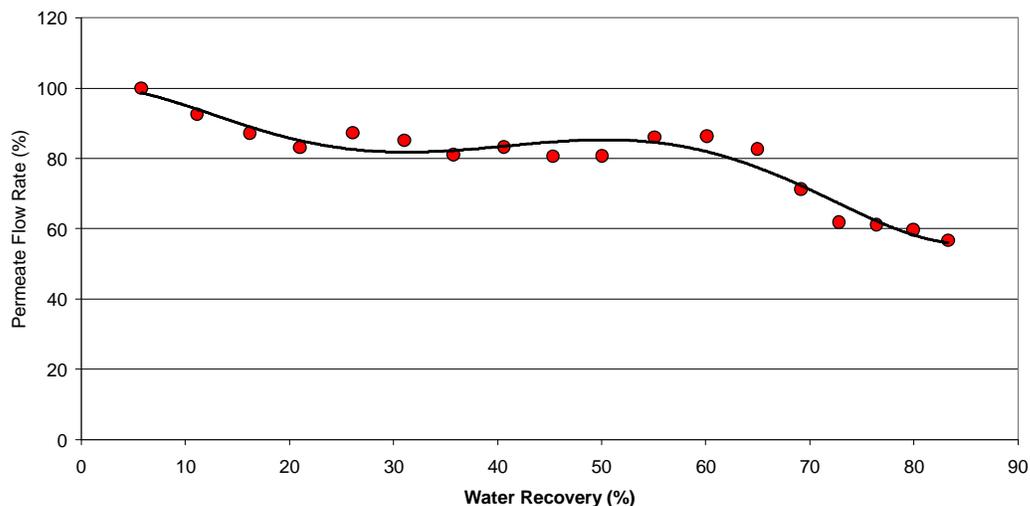
**Figure 4.10:** Calcium concentration as function of water recovery, RO element, with and without antiscalant ( $1.5 \text{ mg L}^{-1}$  Flocon 135), initial flux  $\sim 60 \text{ L h}^{-1}$ .

In Figure 4.9 it can be seen that the flux decreases gradually and that the characteristic sharp drop in permeate flux at the onset of scaling seen in other scaling studies (Zach-Maor et al. 2008) did not occur for the horticultural wastewater. This suggests that scaling did not take place for this wastewater at water recoveries up to approximately 85%. This conclusion is supported by the calcium concentration measurements on the concentrate in the wastewater reservoir (Figure 4.10), which are not lower than the expected calcium concentration in the absence of scaling.

On the basis of these results it can be concluded that calcium concentrations up to  $400 \text{ mg L}^{-1}$  can be run through the RO concentrate stream without scaling.

### NF scaling tests

The influence of water recovery on the NF permeate flux in the presence of  $1.0 \text{ g L}^{-1}$  PAA is shown in Figure 4.11. The calcium concentration of water in the wastewater reservoir during the course of the experiment is shown in Figure 4.12.

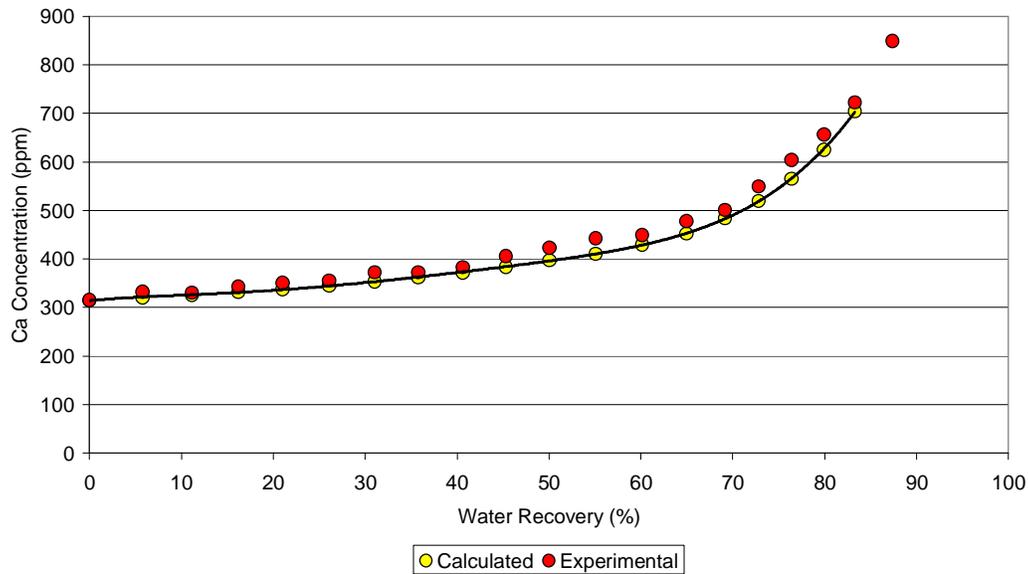


**Figure 4.11:** Permeate flux as function of water recovery, NF element, initial PAA dose of  $1 \text{ g L}^{-1}$  PAA, initial flux of  $\sim 60 \text{ L h}^{-1}$

The flux decline seen in Figure 4.12 can be seen to be different to that for the RO (Figure 4.9). An increase in water recovery to 20% decreased the flux to 80% of its starting value. This flux decline was found to occur at approximately 70% water recovery for the RO. The flux also levels off at 80% to about 65% water recovery, and then drops sharply to 60% between 65% and 75% water recovery. The flux then seems to remain at 60% up to 85% water recovery. This unusual behaviour may be attributable to the adsorption of PAA onto the membrane and possibly the formation of polyacrylate bylayers.

The decline in flux at water recoveries between 65% and 75% water recoveries does not continue at higher water recoveries, suggesting that scaling is not taking place. This conclusion is supported by the calcium concentration measurements on the concentrate in the wastewater reservoir (Figure 4.12), which are not lower than the expected calcium concentration in the absence of scaling. Nevertheless, a flux decline to 60% of the original is not favourable. A water recovery upper limit of

approximately 65% will be used in modelling (Section 4.4.3.2). This equates to a calcium concentration of 500 mg L<sup>-1</sup>.



**Figure 4.12:** Calcium concentration as function of water recovery, NF element, initial PAA dose of 1 g L PAA, initial flux of ~ 60 L h<sup>-1</sup>

#### 4.4.3.2 Modelling of Product Water

The rejection data presented in Section 4.3.3 was used to calculate the expected product water concentration of the key wastewater parameters Na, K, Mg, Ca, N, TDS, EC and SAR. The likely product water concentration of P was not modelled due to its low starting concentration in the wastewater.

#### **ESNA Element**

Table 4.2 (a) shows the modelled expected product water concentration. It can be seen that the ESNA element is not able to decrease the Na levels of the wastewater to below that of the nutrient solution (53 mg L<sup>-1</sup>, see Table 1.1). It can be seen PAA addition makes little or no difference to the concentration of wastewater constituents. The lowest Na concentration (65 mg L<sup>-1</sup>) was achieved at 19 L·2h<sup>-1</sup> and 24 % water recovery. The highest Ca concentration (72 mg L<sup>-1</sup>) was achieved at 39 L m<sup>-2</sup>h<sup>-1</sup>, and 24% water recovery.

Table 4.2(b) shows the retention of the wastewater constituents, expressed as a percentage of the starting wastewater concentration for the ESNA element. Generally, it can be seen that the ESNA element can achieve high nutrient (Ca and Mg) retention in the product water. The Na retention, however, is also considerable.

## **SR2 Element**

Table 4.3(a) shows that the SR2 element is able to decrease the Na levels to 19 mg L<sup>-1</sup> in the absence of added PAA. It can also be seen that a 1.0 g L<sup>-1</sup> PAA addition increases the Ca and Mg concentration of the product from 15 mg L<sup>-1</sup> and 16 mg L<sup>-1</sup> respectively to 56 mg L<sup>-1</sup> and 67 mg L<sup>-1</sup> respectively.

Table 4.3(b) shows the retention of the wastewater constituents, expressed as a percentage of the starting wastewater concentration for the SR2 element. It can be seen that at the highest PAA dose (1.0 g L<sup>-1</sup>) the 81% of the Ca is retained in the product water. Sodium retention at 1.0 g L<sup>-1</sup> PAA was 27% of the starting wastewater concentration. In the absence of PAA, nutrient retention is very low.

It is important to note that the PAA is expected to be totally rejected by the NF element, thereby ending up in the product water (see Figure 1.1) and finally being reused. A small addition of PAA would be needed to replace that adsorbing on the plant medium (scoria) and that being biodegraded by organisms in the plant medium.

## **Comparison of NF-RO treatment to RO only Treatment**

### ***Product Water Production Rate***

In Table 4.4(a), the modelled product water constituent concentration for the NF-RO runs that gave rise to the lowest Na concentration and highest Ca concentration are compared to what can be achieved with RO only.

The RO only control modelled here represents a situation where the NF elements are left in place, but their rejection is set to zero for all wastewater constituents. In such a control scenario, the NF elements are doing nothing other than divert a proportion of the water to the product water, and a proportion of the water to the RO train. Comparison of this RO only control results to the experimental results, thus, shows the individual influence of the NF and RO trains on the water quality. For all the runs where Ca NF rejection is high, it can be seen that the RO-only option uses fewer RO elements than the NF-RO option. In such situations the NF element diverts calcium to the product water, allowing more RO elements to be used before the limiting calcium concentration (400 mg L<sup>-1</sup>) is reached in the concentrate stream.

Table 4.4(a) shows that for the ESNA element, NF-RO treatment can achieve considerably higher production rates (% of feed volume) than can be achieved with RO alone. The concentration of all wastewater constituents is lower for the RO –only control than for the NF-RO scenario. It can also be seen that there is little benefit from a production rate perspective in using NF-RO treatment using the SR2 NF element in the absence of PAA addition over the RO only scenario. The addition of PAA, however, significantly improves the production rate and nutrient concentration (Ca and Mg) over what can be achieved with the RO only scenario. The Na level is slightly higher for the NF-RO than the RO only scenario.

### ***Retention of Wastewater Constituents in Product Water***

Table 4.4(b) shows how much greater the nutrient concentration is for the NF-RO option than for the RO only option. With the ESNA element, 80 to 90% of the nutrients can be retained in the product water with the NF-RO option. This compares

to approximately 20 % for the RO –only option. Sodium retention using NF-RO, however, is more than double that for the RO-only option.

With the SR2 element in the absence of PAA addition, approximately 20% of the nutrients can be retained in the product water with the NF-RO option. This compares to approximately 10 % for the RO –only option. Sodium retention is approximately the same for the NF-RO and RO-only options.

Addition of PAA greatly increases Ca and Mg retention – 81% and 65% respectively. This compares to approximately 20 % for the RO –only option. Sodium retention using NF-RO, however, is slightly higher than that for the RO-only option.

**Table 4.2(a):** Modelled product water **concentration (mg L<sup>-1</sup>)** for MF-NF-RO treatment of wastewater using the **ESNA** NF element

Pre-treatment	Flux (L m <sup>-2</sup> h <sup>-1</sup> )	Water Recovery (%)	Number of NF element	Number of RO elements	Concentration (mg L <sup>-1</sup> )								Production Rate (% of feed)
					Na	K	Mg	Ca	N	TDS	EC	SAR	
none	20	24	9	7	57	142	66	41	2	834	1014	1.3	92
0.1 g L <sup>-1</sup> PAA	20	24	9	8	58	154	56	39	2	986	1015	1.3	95
0.2 g L <sup>-1</sup> PAA	20	25	9	9	58	184	52	41	2	1272	1028	1.4	96
none	19	24	8	7	65	165	71	62	3	1054	1127	1.3	93
none	31	25	7	9	70	178	71	68	5	1122	1289	1.4	96
<b>none</b>	<b>39</b>	<b>24</b>	<b>7</b>	<b>9</b>	<b>84</b>	<b>189</b>	<b>75</b>	<b>72</b>	<b>4</b>	<b>1197</b>	<b>1243</b>	<b>1.7</b>	<b>96</b>
none	20	30	6	7	65	153	63	63	3	992	1097	1.4	93
none	22	22	8	8	72	173	68	65	3	1075	1228	1.5	95

**Table 4.2(b): Modelled retention (%) of wastewater constituents in product water for MF-NF-RO treatment using the ESNA NF element**

Pre-treatment	Flux (L m <sup>-2</sup> h <sup>-1</sup> )	Water Recovery (%)	Number of NF element	Number of RO elements	Retention in Product Water (%)						
					Na	K	Mg	Ca	N	TDS	EC
none	20	24	9	7	41	44	74	62	25	53	49
0.1 g L <sup>-1</sup> PAA	20	24	9	8	42	48	69	67	25	56	48
0.2 g L <sup>-1</sup> PAA	20	25	9	9	42	57	65	78	25	69	48
none	19	24	8	7	43	49	81	79	25	57	52
none	31	25	7	9	51	55	83	85	38	64	59
<b>none</b>	<b>39</b>	<b>24</b>	<b>7</b>	<b>9</b>	<b>57</b>	<b>63</b>	<b>86</b>	<b>90</b>	<b>33</b>	<b>70</b>	<b>56</b>
none	20	30	6	7	43	47	74	78	25	56	50
none	22	22	8	8	48	53	78	82	27	59	56

**Table 4.3(a):** Modelled product water **concentration** (mg L<sup>-1</sup>) and production rate for MF-NF-RO treatment using the **SR2** NF element

Pre-treatment	Flux (L m <sup>-2</sup> h <sup>-1</sup> )	Water Recovery (%)	Number of NF element	Number of RO elements	<b>Concentration (mg L<sup>-1</sup>)</b>								Production Rate  (% of feed)
					Na	K	Mg	Ca	N	TDS	EC	SAR	
none	20	25	10	5	19	42	17	12	1	251	288	0.8	84
0.1 g L <sup>-1</sup> PAA	20	25	10	5	18	46	18	14	1	318	239	0.8	84
none	20	25	10	6	17	36	15	11	1	250	284	0.8	89
0.2 L <sup>-1</sup> PAA	20	25	10	6	19	52	20	17	1.5	399	303	0.7	89
none	20	25	10	4	19	43	16	15	1	296	296	0.8	77
0.5 g L <sup>-1</sup> PAA	19	24	10	5	21	70	27	35	1	664	360	0.7	84
0.75 g L <sup>-1</sup> PAA	19	24	9	6	27	112	40	49	1	902	457	0.7	89
1.0 g L <sup>-1</sup> PAA	19	24	7	8	42	207	56	67	2	1322	687	0.9	95

**Table 4.3(b): Modelled retention (%) of wastewater constituents in product water (%) for MF-NF-RO treatment using the SR2 NF element**

Pre-treatment	Flux (L m <sup>-2</sup> h <sup>-1</sup> )	Water Recovery (%)	Number of NF element	Number of RO elements	Retention in Product Water (%)						
					Na	K	Mg	Ca	N	TDS	EC
none	20	25	10	5	14	14	19	20	10	15	14
0.1 g L <sup>-1</sup> PAA	20	25	10	5	13	15	22	24	11	18	11
none	20	25	10	6	13	14	18	19	13	16	14
0.2 L <sup>-1</sup> PAA	20	25	10	6	15	20	25	31	19	22	14
none	20	25	10	4	13	13	18	18	10	17	13
0.5 g L <sup>-1</sup> PAA	19	24	10	5	14	21	31	45	9	27	15
0.75 g L <sup>-1</sup> PAA	19	24	9	6	18	34	48	64	10	32	18
1.0 g L <sup>-1</sup> PAA	19	24	7	8	27	63	64	81	18	42	25

**Table 4.4(a):** Comparison of modelled product water **concentration** (mg L<sup>-1</sup>) and production rate for MF-NF-RO treatment, and for RO only control

Pre-treatment	NF Element	Flux (L m <sup>-2</sup> h <sup>-1</sup> )	Water Recovery (%)	Number of NF element	Number of RO elements	Concentration (mg L <sup>-1</sup> )							Production Rate (% of feed)	
						Na	K	Mg	Ca	N	TDS	EC		SAR
none	ESNA	19	24	8	7	65	165	71	62	3	1054	1127	1.3	93
RO only Control	ESNA			8	4	26	58	15	14	2	321	371	1.2	79
none	ESNA	39	24	7	9	84	189	75	72	4	1197	1243	1.7	96
RO only Control	ESNA			7	4	31	62	18	16	2	357	457	1.2	79
none	SR2	20	25	10	4	19	43	16	15	1	296	296	0.8	77
RO only Control	SR2			10	4	15	33	9	8	1	178	225	0.9	77
1.0 g L <sup>-1</sup> PAA	SR2	19	24	7	8	42	207	56	67	2	1322	687	0.9	95
RO only Control	SR2			7	4	32	152	18	18	2	643	550	1.3	79

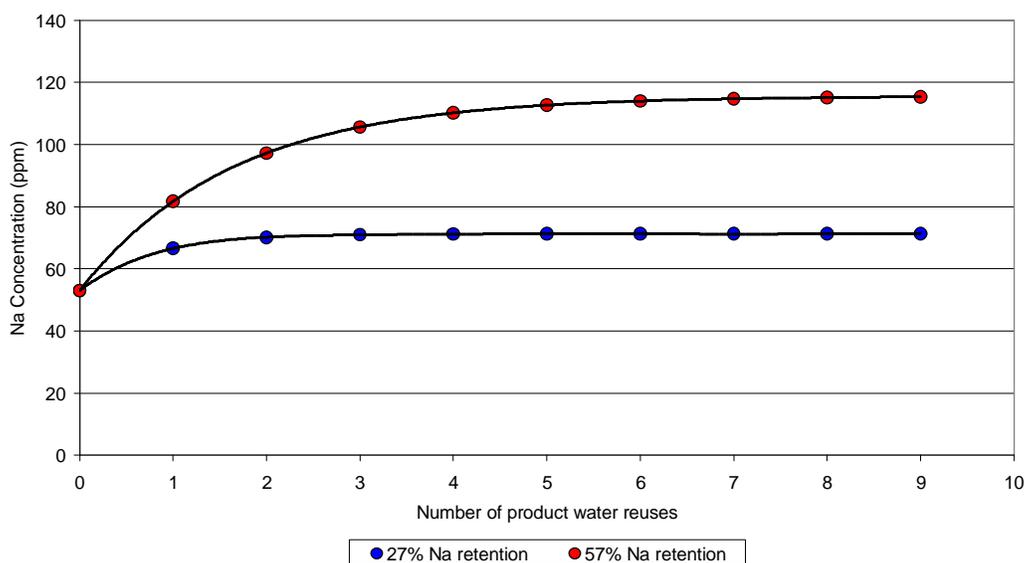
**Table 4.4(b):** Comparison of modelled product water **retention of product water constituents (%)** for MF-NF-RO treatment, and for RO only control

Pre-treatment	NF Element	NF Flux (L m <sup>-2</sup> h <sup>-1</sup> )	NF Water Recovery (%)	Number of NF element	Number of RO elements	Retention in Product Water (%)						
						Na	K	Mg	Ca	N	TDS	EC
none	ESNA	19	24	8	7	43	49	81	79	25	57	52
RO only Control	ESNA			8	4	17	17	17	18	17	17	17
none	ESNA	39	24	7	9	57	63	86	90	33	70	56
RO only Control	ESNA			7	4	21	21	21	20	17	21	21
none	SR2	20	25	10	4	13	13	18	18	10	17	13
RO only Control	SR2			10	4	10	10	10	10	10	10	10
1.0 g L <sup>-1</sup> PAA	SR2	19	24	7	8	27	28	64	81	18	42	25
RO only Control	SR2			7	4	20	20	21	22	18	20	20

### Expected Product Water Composition

It was shown in section 4.2 that the sampled wastewater used in the experiments had an elevated Na content ( $130 \text{ mg L}^{-1}$ ), considerably above that of the nutrient solution ( $53 \text{ mg L}^{-1}$ ), indicating that the plant uptake of Na is low and that its concentration increases above that of the nutrient solution by evaporation. The net concentration factor was  $130/53 = 2.45$ . It must, however, be noted that since water loss varies considerably between crops grown, stage of growth, temperature, relative humidity, day length and hydroponic system used, this concentration factor and the water quality is expected to also vary.

The calculated expected Na concentration with repeated reuse cycles, using a concentration factor of 2.45, with 57% Na retention (highest Ca retention ESNA element result) and 27% Na retention (highest Ca retention SR2 result), 5% volume loss during treatment, make up of total lost volume (evaporation plus treatment) with fresh water with zero sodium content, and  $53 \text{ mg/L}$  sodium addition (Na content of nutrient solution, Table 4.1) at each reuse cycle, are shown in Figure 4.13.



**Figure 4.13:** Calculated expected Na concentration with repeated reuse cycles, using a concentration factor of 2.4, with a starting Na concentration of  $53 \text{ mg L}^{-1}$ , 57% Na retention (highest Ca retention ESNA element result) and 27% Na retention at each reuse cycle (highest Ca retention SR2 result).

It can be seen that for a 57% retention at each reuse cycle, the Na concentration progressively increases and levels off at  $117 \text{ mg L}^{-1}$  after approximately 6 reuse cycles. For a 27% Na retention at each reuse cycle, the Na concentration levels off at  $71 \text{ mg L}^{-1}$  after approximately 3 reuse cycles.

The salt tolerance of tomato plants is expressed as chloride tolerance. This upper limit is  $887 \text{ mg L}^{-1}$  (National Resources Management Ministerial Council 2006), which equates to  $582 \text{ mg L}^{-1}$  Na. The calculated Na levels after multiple reuse cycles is well below this upper limit, indicating that sodium (or chloride) toxicity is unlikely to occur.

It is important to also consider that there is also an upper limit on the EC of the reused water. The EC of the nutrient solution was approximately  $3,000 \text{ uS cm}^{-1}$ . In

order to keep the EC of the nutrient solution close to  $3,000 \text{ uS cm}^{-1}$ , it is important to keep the Na content of the product water as low as possible. The calculated Na levels of  $70 \text{ mg L}^{-1}$  and  $115 \text{ mg L}^{-1}$  for nutrient solution prepared with the recycled water are respectively, 17 and  $62 \text{ mg L}^{-1}$  higher than nutrient solution prepared using fresh water ( $53 \text{ mg L}^{-1}$ ). The 17 and  $62 \text{ mg L}^{-1}$  Na levels equate to  $43 \text{ mg L}^{-1}$  and  $158 \text{ mg L}^{-1}$  NaCl respectively. These salt levels would be expected to elevate the EC by approximately 64 and  $237 \text{ uS cm}^{-1}$  respectively.

### ***Management Issues***

When using fresh water to make up the nutrient solution, the grower knows exactly how much of each nutrient is present in the solution before applying it to the crop, and can increase or decrease the levels of individual nutrients according to the grower's knowledge and experience of the crop's needs at different stages of development. Unless the grower undertakes an expensive water testing regime, this level of control is not available to the grower when using recycled water containing nutrients. The concentration of nutrients in the recycled water depends on water loss due to evaporation and on the crop nutrient uptake, both of these being highly dependent on crop variety grown, stage of growth, temperature, relative humidity and day length, as well as treatment plant performance. The concentration of nutrients in the recycled water is therefore expected to vary. Management of nutrient solution composition and application rate would require preliminary testing to determine what this variation is likely to be under a variety of expected environmental conditions.

#### 4.4.4 Summary and Conclusions – Scaling Tests and Modelling

##### **Scaling Tests**

The Ca limits for the horticultural wastewater were found to be:

- 400 mg L<sup>-1</sup> for the RO train
- 500 mg L<sup>-1</sup> for the NF train

##### **Modelling**

###### **ESNA Element**

PAA addition makes little or no difference to the concentration of wastewater constituents with the ESNA element.

The lowest Na retention obtained with the ESNA element was 43% of the original Na concentration at 19 Lm<sup>-2</sup>h<sup>-1</sup> flux and a 24% water recovery. The Ca retention under these conditions was 81% of original Ca.

The highest Ca retention with the ESNA element was 90% of the original Ca concentration at 39 Lm<sup>-2</sup>h<sup>-1</sup> flux and a 24% water recovery. The Na retention under these conditions was 57% of original Na.

###### **SR2 Element**

The lowest Na retention obtained with the SR2 element was 13% of the original Na concentration in the absence of added PAA. The Ca retention under these conditions was 18% of original Ca.

The highest Ca retention with the SR2 element was 81% of the original Ca concentration at 1.0 g L<sup>-1</sup> PAA. The Na retention under these conditions was 27% of original Na.

###### **Product-water Production Rate**

For the ESNA element, NF-RO treatment can achieve considerably higher production rates (93 to 96% of feed volume) than can be achieved with RO alone (79% of feed volume).

For the SR2 element

- PAA addition is required for the NF-RO treatment process to give rise to a greater product water production rate than RO treatment
- NF-RO treatment with 1 g L<sup>-1</sup> PAA can achieve considerably higher production rates (95% of feed volume) than can be achieved with RO alone (79% of feed volume).

###### **Sodium build up**

For a 57% retention at each reuse cycle, the Na concentration is expected to progressively increase and levels off at 117 mg L<sup>-1</sup> after approximately 6 reuse cycles. For a 27% Na retention at each reuse cycle, the Na concentration is expected to level off at 71 mg L<sup>-1</sup> after approximately 3 reuse cycles.

## 4.5 Summary and Conclusions

This part of the report deals with the application of MF-NF-RO treatment to horticultural wastewater. The feasibility of treating wastewater from a hydroponic tomato farm for on-farm reuse is investigated.

The two highest nutrient recovery treatment options presented in this study were:

- 63% K, 86% Mg, 90% Ca, 57% Na retention in product water (ESNA element, 39 Lm<sup>-2</sup>h<sup>-1</sup> flux and a 24% water recovery)
- 63% K, 64% Mg, 81% Ca, 27% Na retention in product water (SR2 element, 1.0 g L<sup>-1</sup> PAA).

For a 57% Na retention at each reuse cycle, the Na concentration in the nutrient solution is expected to progressively increase and levels off at 117 mg L<sup>-1</sup> after approximately 6 reuse cycles. For a 27% Na retention at each reuse cycle, the Na concentration is expected to level off at 71 mg L<sup>-1</sup> after approximately 3 reuse cycles. These sodium levels are unlikely to be harmful to plant growth or yield.

It was demonstrated that NF-RO treatment may achieve product water production rates that are 93 to 95% of the feed volume. This is considerably above what can be achieved with RO only treatment (79% of feed volume).

## 4.6 References:

National Resource Management Ministerial Council, Environment Protection and Heritage Council, Australian health Ministers' Conference, National Water Management Strategy, National Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 1) 2006

Zach-Maor, A., Semiat, R., Rohardianto, A., Cohen, Y. and Gray, S., 2008, Diagnostic analysis of RO desalting treated wastewater, *Desalination* 230, 239-247.

## 5 Costing and Feasibility Study

### 5.1 Introduction

The options submitted for the costing feasibility study pertain to NF-RO treatment with and without PAA NF enhancement. Two control options, consisting of RO only treatment, were also submitted for costing. These controls are designed to show how RO would perform with respect to both water quality and product water production rate. The NF-RO Cases were costed for product water production rate of 1 ML/day. Due to the lower achievable RO water recovery in the absence of NF treatment, the product water production rate from the RO only control cases is less than that of their corresponding NF-RO case.

The following treatment options were selected from experimental data and modelling for this costing feasibility study:

**Case 1:** NF-RO, no PAA addition, Koch SR2, modelled product water composition = 19.2% NF concentrate + 80.8% RO permeate, 1 ML/day product water production rate.

**Case 2:** NF-RO, 0.2 g L<sup>-1</sup> PAA addition, Koch SR2, modelled product water composition = 23.5 % NF concentrate + 76.5% RO permeate, 1 ML/day product water production rate.

**Case 3:** RO-only control for Option 2. Modelled product water composition = 23.5 % raw wastewater + 76.5% RO permeate, calculated product water production rate.

**Case 4:** NF-RO, 0.7 g L<sup>-1</sup> PAA addition, Koch SR2, modelled product water composition = 30 % NF concentrate + 70% RO permeate, 1 ML/day product water production rate.

**Case 5:** RO-only control for Option 4 (see p. 18). Modelled product water composition = 30 % raw wastewater + 70% RO permeate, calculated product water production rate.

The experimental flux and modelled NF and RO recoveries for the above cases are shown in Table 5.1

**Table 5.1:** Flux and recoveries for selected costing options

	Case 1	Case 2	Case 3	Case 4	Case 5
<b>NF system flux (lmh)*</b>	17.5 ± 5	24.0 ± 5	Not Applicable	18.0 ± 5	Not Applicable
<b>RO system flux (lmh)*</b>	23.5 ± 5	17.6 ± 5	17.6 ± 5	14.4 ± 5	14.4 ± 5
<b>NF system recovery (%)</b>	89.3	79.5	Not Applicable	71.3	Not Applicable
<b>RO system recovery (%)</b>	51.0	83.2	65.7	94.2	65.7

\* lmh = litre/m<sup>2</sup>/hour

The modelled expected water quality and production rate data for these treatment options is shown in Table 5.2. (N.B.: This modelled water quality data is slightly different to that presented in Table 3.5 (p.21) as the experiments were performed under different flux and water recovery conditions.)

**Table 5.2:** Modelled expected water quality and production rate data for costed treatment options.

Treatment	PAA Conc (g/L)	Concentration								SAR	Production rate (% of feed)
		(mg L <sup>-1</sup> )						(μS cm <sup>-1</sup> )			
		Na	K	Mg	Ca	N	P	TDS	EC		
NF-RO	0	74	8	8	11	7	19	266	439	4.2	56
NF-RO	0.2	78	35	16	25	5	5	519	503	3.0	87
RO-only control 1		67	28	7	8	5	5	331	446	4.2	68
NF-RO	0.7	118	128	22	30	6	8	1071	766	4.0	96
RO-only control 2		89	93	8	11	6	7	601	644	5.1	67

The basis and assumptions used in this costing are given in section 2.4 and Table 2.7 of the costing document (Appendix 3).

Cases 1, 2 and 4 were costed for a product water production rate of 1 ML/day. Cases 3 and 5 represent control scenarios for Cases 2 and 4 respectively and are designed to reflect what could be achieved by treatment with RO only. In cases 3 and 5 the plant is essentially an RO plant and the RO permeate is blended with raw wastewater rather than an NF concentrate. The ratio of NF concentrate to RO permeate in cases 2 and 4 is the same as the ratio of raw water to RO permeate in cases 3 and 5 respectively. The number of RO elements, and therefore the water recovery that can be achieved, however, is less in cases 3 and 5 than in cases 2 and 4, due to the higher calcium concentration reaching the RO train in cases 3 and 5, requiring the limiting of the RO water recovery in the modelling. The product water production rate for the control cases was calculated and was found to be less than that of the corresponding NF-RO case. The calculated annual production of product water for the control cases can be compared to that of the cases 1, 2 and 4 in Table 5.3.

**Table 5.3:** Annual production of product water for costed options.

	Case 1	Case 2	Case 3	Case 4	Case 5
Annual Production of Product Water (ML/yr)	360	360	284	360	251

## 5.2 Costing Summary

The power, chemical and capital expenditure for these options is summarised in Table 5.4. The full costing report by CH2MHILL is presented in its entirety in Appendix 3 (p. 97). A breakdown of the operating expenditure for each option is given in Table 5.5

**Table 5.4:** Power, chemical and capital expenditure for costed options

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5
Power Cost (\$/ML of product water)	231	132	95	93	80
Chemical Cost (\$/ML of product water)	61	437	35	1,298	33
Capital expenditure* (\$)	1,569,830	1,315,026	638,476	1,315,026	638,476

\* Average of three estimates

**Table 5.5:** Estimated Annual Operating Costs for each Option

Operating Expenditure (OPEX)					
	Case 1	Case 2	Case 3	Case 4	Case 5
Power Cost	\$83,040	\$47,390	\$26,870	\$33,580	\$19,980
Chemical Cost	\$21,767	\$157,468	\$9,984	\$466,974	\$8,291
Repair & Maintenance	\$50,609	\$41,647	\$15,815	\$41,647	\$15,815
Labour	\$89,180	\$89,180	\$89,180	\$89,180	\$89,180
Sub-Total	\$244,596	\$335,686	\$141,849	\$631,382	\$133,266
Contingency	\$48,919	\$67,137	\$28,370	\$126,276	\$26,653
Total OPEX per annum	\$293,515	\$402,823	\$170,219	\$757,658	\$159,920

## 5.3 Discussion

### 5.3.1 Effect of PAA addition

It can be seen in Table 5.2 that the addition of PAA increases the product water production rate. PAA addition effectively allows more calcium to be diverted to the product water and away from the RO stream, thereby allowing more RO elements to be used, resulting in a higher RO train water recovery. To facilitate comparison, however, the costing for Cases 1, 2 and 4 has been performed at constant product water production rate (1 ML/day). Low product water production rate would be expected to be reflected in higher power costs. A process that, for example, has a production rate close to 50% of the feed volume would be expected to have twice the power cost, per ML of product water, of a process that has production rate of close to 100 % of feed volume. The modelling of experimental results shown in Table 5.2, show that the production rate for Case 1 is only 65% of the feed volume, whereas the production rate for cases 2 and 4 are 87% and 96% of feed volume respectively. The power consumption *per ML of product water*, therefore, can be seen to decrease with increasing PAA concentration.

It must be emphasised that the power costs quoted in Table 5.2 were obtained with Dow- Filmtec's ROSA software which has no information on the Koch SR2 NF elements used in the experiments. In the ROSA modelling, the more power demanding NF90-400 nanofiltration membrane was used as a surrogate for the Koch SR2-400. A comparison of the power requirements of the NF90 (from ROSA software) and the SR2 element (from experiment) is shown in Table C1, Appendix C, p.142. Table C1 shows two effects – an increase in operational pressure with addition of PAA, and lower operational pressures for the Koch SR2 than for the NF90. Taking this into consideration the NF contribution to the NF-RO process power costs, the power cost for Cases 1, 2 and 4 should be 174 to 179 \$/ML (62,640 – 64,440 \$/yr), 107 to 113 \$/ML (38,520 – 40,680 \$/yr) and 82 to 88 \$/ML (29,520 – 31,680 \$/yr) respectively.

The chemical costs associated with PAA addition are considerable. Based on the data presented in Table 5.3, the cost associated with PAA addition increase the chemical costs from approximately 10% of operating expenditure (Case 1) to approximately 40% of operating expenditure (Case 2) and approximately 60% of operating expenditure (Case 4). In Table 5.3, the chemical costs of NF-RO treatment in the absence of PAA are approximately double those of RO-only treatment. If the product water production rates in Table 5.3 are taken into account, the chemical costs of NF-RO treatment (Case 1, \$21,767) is 1.7 times the cost of RO-only treatment (Case 3, \$9,984 x 360/284 = \$12,655).

Primarily due to the chemical cost component, the operating expenditure of Case 2 (0.2 g/L PAA) and Case 4 (0.7 g/L PAA) were respectively estimated to be 1.4 times and 2.6 times the operating expenditure of Case 1 (no PAA addition).

The higher chemical costs associated with PAA addition would be expected to be mitigated by the higher quality of the product water, the larger quantity of product water and the lower volume of waste brine (see Table 5.2). The expected waste brine volume at 0.2 g/L PAA (13% of feed volume) is expected to be 0.3 times that in the absence of PAA addition (44% of feed volume). The expected waste brine volume at 0.7 g/L PAA (4% of feed volume) is expected to be 0.1 times that in the absence of PAA addition (see Table 5.2).

### **5.3.2 Effect of NF treatment**

The capital expenditures for the costed options are shown in Table 5.4. As expected, the capital expenditure and chemical costs for the NF-RO options (Cases 1, 2 and 4) are considerably higher than that for the RO only control options (cases 3 and 5). Capital expenditure and chemical costs of the NF-RO Option 1 (no added PAA), are more than double those of the RO only controls.

In the absence of PAA, the Koch SR2 NF-RO treatment (Case 1) is no better than RO only treatment. The production rate for the Case 1 NF-RO treatment option (56% of feed volume) is less than that for the RO only options (Case 3: 68% and Case 5: 67%) and the water quality is similar. Other NF-RO treatment options with no PAA addition, however, promise considerably higher product water production rate and higher nutrient retention in the product water than Case 1, but with moderately higher sodium, EC and SAR. For ease of comparison with the current costing data, the data previously presented in Tables 3.5, page 19 is presented again in Table 5.6.

**Table 5.6:** : Modelled expected water quality and production rate data for NF200, NF270 and DK NF-RO treatment options.

NF Membrane	Concentration								SAR	Production rate (% of feed)
	(mg L <sup>-1</sup> )						(μS cm <sup>-1</sup> )			
	Na	K	Mg	Ca	N	P	TDS	EC		
SR2	74	8	8	11	7	19	266	439	4.2	56
NF200	120	13	18	21	8	40	525	807	4.7	81
NF270	116	12	24	22	6	26	384	733	4.0	80
DK	170	18	27	36	8	20	719	1012	5.2	98

It can be seen in Table 5.6 that the product water EC and SAR of the NF-RO treatment using the DK is considerably higher than that of the other options. The water quality and the high operational pressures required for this NF element (see Table 3.7, p.22) make this option considerably less attractive than the NF200 and NF270 options.

The NF200 and NF270 options have similar production rates to those seen with the 0.2 g/L PAA (see Table 5.2). These options would be expected to have similar energy and capital costs to Case 2, with the chemical cost of Case 1. Using the data in Table 5.5, the operating expenditure of these options would be expected to be \$402,823 (Case 2 operating expenditure) - \$157,468 (Case 2 chemical costs)+ \$21,767 (Case 1 chemical costs) = \$267,122.

#### 5.4 Conclusions- Costing and Feasibility Study

This costing, together with consideration of the expected water quality, has shown that:

- NF-RO treatment requires a capital expenditure that is approximately double that of RO only, but gives better water quality and lower brine volumes for disposal than for RO only treatment
- NF-RO treatment using PAA addition increase the chemical costs from approximately 10% of operating expenditure with no added PAA, to approximately 40% of operating expenditure at 0.2 g/L, and approximately 60% of operating expenditure at 0.7 g/L. For the Koch SR2 NF membrane element, better water quality and lower brine volumes for disposal were achieved for NF-RO treatment with PAA addition than for NF-RO treatment in the absence of PAA
- NF-RO treatment in the absence of PAA addition using the NF200 or NF270 elements offers a less expensive alternative but with a moderately worse water quality and brine volumes for disposal

Estimates of the costs associated with the two treatment options that were found to yield the best combination of water quality, production rate and cost are summarized and compared to RO only treatment in Table 5.7.

**Table 5.7:** Summary of estimated costs and expected water quality for a 1 ML/day treatment plant

Option description	NF Element	Units	Treatment Option		
			1	2	3
			Koch SR2	NF270	BWRO
	PAA dose	g/L	0.2	0	0
Costs	Power	\$/yr	41k <sup>a</sup>	48k <sup>b</sup>	34k <sup>c</sup>
	Chemical	\$/yr	158k	22k <sup>b</sup>	13k <sup>c</sup>
	Total Operating	\$/yr	396k	268k <sup>b</sup>	215k <sup>c</sup>
	Capital	\$	1.3M	1.3M <sup>b</sup>	0.82M <sup>c</sup>
Water Quality	Na	mg L <sup>-1</sup>	78	116	67
	K	mg L <sup>-1</sup>	35	12	28
	Mg	mg L <sup>-1</sup>	16	24	7
	Ca	mg L <sup>-1</sup>	25	22	8
	N	mg L <sup>-1</sup>	5	6	5
	P	mg L <sup>-1</sup>	5	26	5
	TDS	mg L <sup>-1</sup>	519	384	331
	EC	µS cm <sup>-1</sup>	503	733	446
	SAR		3.0	4.0	4.2
Waste Brine Volume		% of feed volume	13	20	32

- a) Calculated from the values given in Table 5.5 and the pressure data in Table C1, Appendix 3 (p.140).
- b) Case 2 power cost, Case 1 chemical cost, Operating cost = Case 2 operating costs – Case 2 chemical costs + Case 1 chemical costs
- c) Calculated from values in Table 5.5 and production rate data in Table 5.3 = Value from Table 5.5 x 360/283

MF-NF-RO treatment using the NF270 element in the absence of PAA addition has 1.6 times the capital cost, 1.7 times the chemical costs and 1.4 times the power cost of RO only treatment, and promises to provide product water with moderate Na (116 mg L<sup>-1</sup>) and EC values (733 µS cm<sup>-1</sup>), and higher P, Ca, Mg and K content (5.2, 2.7, 3.4, and 2.3 times the RO-only values respectively) and lower waste brine volumes (0.6 times the RO-only values) than RO-only treatment.

Lower Na (78 mg L<sup>-1</sup>) and EC values (503 µS cm<sup>-1</sup>), and waste brine volumes (0.4 times the RO-only values) can be achieved with PAA addition, but this is at considerably higher chemical costs – 7 times the NF270 option chemical cost and 12 times the RO-only option chemical costs, increasing the annual operating costs from \$268k to \$396k.

## **6 Conclusions and Recommendations**

This research has provided evidence that MF-NF-RO treatment of wastewater is a feasible and potentially useful alternative to RO-only treatment that promises to provide more and better quality water for irrigation, and a lower waste brine volume than conventional MF-RO treatment. These advantages, however, come at a cost.

MF-NF-RO treatment using the NF270 element in the absence of PAA addition has 1.6 times the capital cost, 1.7 times the chemical costs and 1.4 times the power cost of RO only treatment, and promises to provide product water with moderate Na ( $116 \text{ mg L}^{-1}$  and EC values ( $733 \text{ } \mu\text{S cm}^{-1}$ ), and higher P, Ca, Mg and K content (5.2, 2.7, 3.4, and 2.3 times the RO-only values respectively) and lower waste brine volumes (0.6 times the RO-only values) than RO-only treatment.

Lower Na ( $78 \text{ mg L}^{-1}$ ) and EC values ( $503 \text{ } \mu\text{S cm}^{-1}$ ), and waste brine volumes (0.4 times the RO-only values) can be achieved with PAA addition ( $0.2 \text{ g L}^{-1}$ ), but this is at considerably higher chemical costs – 7 times the NF270 option chemical cost and 12 times the RO-only option chemical costs, increasing the annual operating costs from \$268k to \$396k.

A detailed cost benefit analysis is required to ascertain whether the added expense associated with higher water quality and lower waste brine volume is warranted in terms of the value and yield of the crop and the economic and environmental costs of disposal of the brine.

For field irrigation reuse of the recycled water, if the expense associated with PAA addition are found to be warranted, further research is required into the effect of PAA on soil structure and crop yield, as well as the biodegradation of PAA in soils and the likely effect of its accumulation in the soil over long periods of time.

For on-site reuse of the recycled water to make up hydroponics nutrient solution, if the expense associated with PAA addition are found to be warranted, further research is required to determine the effect of PAA on plant uptake of nutrients and crop yield and the expected loss of PAA through biodegradation and adsorption in the hydroponics system. Regardless of whether PAA is used, further research is also required to determine the optimum management regime required to minimize the potential build-up of plant pathogen organisms in the recycled water, and to give the grower a realistic indication of the variability of the nutrient content of the recycled water.

This research highlights the advantages, disadvantages and potential of MF-NF-RO treatment, and provides data to facilitate the design of membrane desalination processes to meet the water needs of the agricultural and horticultural industry.

## Appendix 1:

### **Feasibility study for the requirement of a Designer Recycled Water system for the Hydroponic Industry in Australia**

September 5, 2006.

By: Dr Daryl Stevens and Jonathan Eccles, Arris Pty Ltd.  
Profs Linda Zou and Stephen Gray, Victoria University  
Prof. Greg Leslie, University of New South Wales



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**Opportunities for Designer Recycled Water  
Stage 2 – Feasibility study and assessment of the hydroponic industry in  
Australia**

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Abbreviations: ABS = Australian Bureau of Statistic, DRW = Designer Recycled Water, Ha = Hectares, KL = kilolitre, ML = megalitre, RO = Reverse Osmosis

## 1. Executive Summary

This report is part of a larger research project designed to assess the possibility of recycling water and nutrients from two sources of wastewater (hydroponic or soil-less culture systems and treated sewage effluent) for use in the hydroponic plant production industry.

The aim of this report is to determine if:

- there is a significant volume of wastewater produced in the hydroponic industry and what is currently done with this wastewater;
- the environmental benefits from recycling the water and nutrients from wastewater (hydroponic and treated sewage effluent) will lead to water efficiencies and better protection of the environment; and
- there are potentially economic gains from developing or improving a system for recycling water for this industry

Through discussion with key members of the hydroponic industry, literature and industry statistics, limited reports summarising the size of the hydroponic industry in Australia were located. However, by integrating Australian Bureau of Statistic data with industry information on water use, estimates of wastewater production and potential economic benefits were made.

- The volumes of water used (26,700 to 189,500 ML/Y) and wastewater produced (37,900 to 94,700 ML/yr) in the hydroponic industry in Australia were estimated to be considerable;
- The economic benefits from recycling water from hydroponic waste were estimated to improve grower profitability in the future, especially if the price of water significantly increases in the future;
- The economic benefits from recycling water from treated sewage would increase substantially if nutrients from the water could also be recycled; and
- Detrimental impact to the environment would be negated by reducing the flow of the hydroponic wastewater and treated sewage water to the environment.

To realise these environmental and economic benefits the challenge is to:

1. Develop a system that uses the water more efficiently (recycles) and reduces the waste volume;
2. Reclaim beneficial nutrients in wastewater at an economic cost; and
3. Concentrate the wastewater volume further and produce a marketable by-product with the salts.

The designer water concept has the potential to satisfy challenges 1 and 2. It can be used in two ways for the horticulture industry: to treat the wastewater generated on site at horticulture greenhouses, and to further treat effluent from the WTPs ie recycled water. The third challenge could be realised by integrating solar drying ponds for the low volume of saline waste (5%) produced and a truly closed system developed. This system would have no detrimental environmental impacts and would ultimately provide economic benefits in the future as wastewater disposal is more tightly regulated and the cost of water increases.

The data recognized the potential for cost savings in fertilisers and that imminent increases in the price of water will make the DRW concept profitable for the hydroponic industry in the future. It should be noted that some growers already use

potable water sources for hydroponic production systems, and in these scenarios, given the cost of the water reclamation process being considered (Table 13) the DRW concept should provide direct environmental and economic benefits to the hydroponic industry and indirect social benefits to the work force that supports this industry, by helping it remain a competitive and profitable industry.

These data confirm that there is a need for the DRW research project to help the hydroponic industry reduce its ecological footprint by improving wastewater management and recycling nutrients and water.

## **2. Background**

Salinity can limit the use of recycled water for agriculture and horticulture. Desalination is often required. However, current technological solutions are not ideal as they remove valuable nutrients and produce high volumes of saline waste streams.

This report is part of a larger research project which assesses the possibility of recycling water and nutrients from two sources of wastewater: hydroponic or soil-less culture and treated sewage effluent. In both cases reverse osmosis (RO) treatment is often required to lower the concentration of ions (salts) for use of the recycled water in hydroponic systems used in a range of horticultural crops. However, RO is not selective with regard to the ions that it removes and nutrients in the wastewater are rejected along with unwanted ions such as sodium and chloride. This process has a high energy and material cost and many valuable nutrients including nitrogen, phosphorus, calcium, magnesium, potassium and sulphate are removed and discharged to the environment where many can have detrimental impacts. Ideally it is desirable to produce the recycled water that retains the nutrient components but without excessive levels of unwanted salts (ie Designer Recycled Water or DRW; Leslie, Stevens *et al.* 2005).

This could be achieved by staging the separation of dissolved inorganic components in the wastewater by a two stage salt separation process of nanofiltration (NF) followed by RO. The larger divalent and trivalent ions are separated by the less energy and cost demanding NF process, and only the permeate of nanofiltration is fed into the RO membrane and contains mainly mono-valent salts and some smaller ions. By changing the various operating conditions, product water with designed nutrient and trace element concentrations can be obtained. This approach aims to achieve the ideal water quality for the proposed use.

The benefits of this proposed process configuration are:

- More beneficial finished product - containing nutrients (phosphates, nitrates, ammonium), major ions, and adjusted sodium absorption ratio.
- More efficient desalination through the removal of scaling ions prior to the reverse osmosis stage. These ions can precipitate on the reverse osmosis membrane, significantly limiting membrane life and water recoveries, and increasing power consumption and running costs.
- Reduced environmental impact of concentrate (waste) disposal through production of a smaller waste volume and the fact that it contains less nutrients.
- More concentrated saline waste of a greater purity which may improve opportunities for refinement of salt products
- More efficient use of our limited water resources.

### 3. Aim

The aim of this report is to determine the:

- Volumes of water used in the hydroponic industry;
- Volumes of wastewater produced in the hydroponic industry and how this wastewater is managed;
- Environmental benefits from recycling the wastewater produced from the hydroponic industry or from treated sewage effluent, from a water efficiency and environmental protection perspective; and
- Potential economic gains from developing a system for recycling water from this industry

These aims were met by:

- Assessing the Australian Hydroponic Industry by conducting random surveys of leading horticulturist on the waste produced using hydroponic systems and how this is currently managed;
- Conducting a literature/industry search and review on the nutrient requirements of agricultural/horticultural applications ;
- Identifying water usage and wastewater volumes through industry data and the Australian Bureau of Statistics, when specific industry data was limited;
- Comparing nutrient/water quality requirements with the technologies to control the nutrient levels and water quality in the recycled water; and
- Evaluating the merit of the multiple staged water treatment process in terms of reducing waste streams and improving resource quality.

## 4. The Australian Hydroponic Industry

### 4.1 Types of hydroponic systems

Hydroponics is a system of growing crops in a soilless system or container, isolated from the ground with all its nutrients in the feed water. Many hydroponic cropping systems are combined with a protective environment allowing total control of the nutrient supply, irrigation and the crop environment. There are many different hydroponic systems used in Australia but the more common are:

#### ***Nutrient Film Technology (NFT)***

This was the original pioneering hydroponics technique. The plants are grown in a constant flow of nutrient enriched water. The water is spread out so as to flow in approximately 1-3mm of depth over a flat surface, creating a film of water, which flows over the root system of the plant in a constant, gentle motion.

The solution is recirculated with the whole solution often being renewed after a few weeks or in the case of short growing crops being dumped at the end of the crop's life.

The term 'closed' system was often used synonymously with NFT but many media based systems are now operating as 'closed' systems.

#### ***Media based***

Media systems involve the nutrient solution being dripped at intervals into an inert material which provides a suitable environment for root development. The most common media are rockwool, sawdust, sand, expanded clay, scoria, perlite/vermiculite and cocopeat. The nutrient solution is applied to the medium in which the plant grows and is then drained off as waste. The

solution is not recirculated and fresh nutrient is applied to the plants each time. This is often referred to as an 'open' system.

### ***Industries using hydroponics***

Currently in Australia there is a range of industries that use hydroponic systems for producing horticultural crops (Figure 1). Many of them are near major capital cities and could potential use water recycled from treated sewage effluent. Crops grown in Australia using the hydroponic system fall into two major commodities, vegetables and cut flowers, and use two major types of production systems:

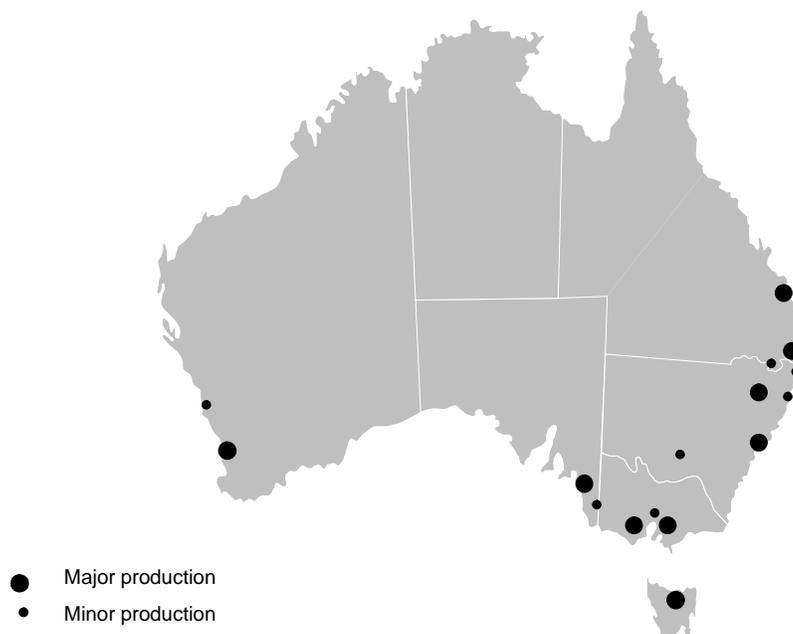
#### Indoor hydroponics – Vegetables

- Tomatoes
- Cucumbers
- Capsicum
- Asian leafy vegetables
- Herbs
- Cut flowers

#### Outdoor hydroponics

- Lettuce
- Asian vegetables
- Herbs

These crops can be grown under various protected cropping materials such as glass, polythene, shade cloth and polycarbonate (collectively referred to as 'greenhouses'). Outdoor hydroponic systems often use shade cloth protection against extreme sunlight and heavy rain or hail. For the purpose of the report, all these structures will be referred to as greenhouses.



**Figure 1 Location of hydroponic horticultural production in Australia**

## 4.2 Industry footprint

### *Area irrigated*

Greenhouse vegetable production statistics are limited across Australia. Most data from ABS give whole of industry or principal commodities information (eg ABS 2006a; ABS 2006b). Information from industry leaders and other reports (HAL 2004; Smith 2005) have been collated to give a best estimated for Australia (Table 1). The data show that Victoria is the largest greenhouse user with approximately 1700 ha of greenhouse production. New South Wales, Qld, SA and WA are the next largest greenhouse users with approximately 800-900 ha (Table 1).

**Table 1:** Greenhouse vegetable production statistics (Estimated for 2005-06)

State	Production areas under greenhouse		Total greenhouse
	Vegetables <sup>A</sup>	Cut flowers <sup>B</sup>	Area per state
	(Ha)	(Ha)	(Ha)
NSW	500	488	988
Vic	250	1,454	1,704
Qld	30	778	808
SA	580	352	932
WA	21	925	946
TAS	10	65	75
NT	Na	15	15
<b>Total</b>	<b>1,391</b>	<b>4,078</b>	<b>5,469</b>

<sup>A</sup> Smith 2005, <sup>B</sup> HAL 2004 assumes 70% of cut flowers are grown in greenhouses. na = not available

### *Water usage*

For vegetables and cut flowers the annual water use in greenhouse production was estimated to be approximately seven times that of broadacre cropping (Table 3). This would be expected for several reasons:

- Greenhouse production uses much more water due to intensive nature of cultivation and nearly all year round production (Table 2);
- Unprotected crops receive rainfall and access soil which has a much greater water holding capacity and can capture and store rainfall. Hydroponics relies on a continual supply of water;
- Denser plantings and larger plants are grown under the optimum conditions in greenhouse (Table 2); and
- Crops are grown in greenhouses 80 to 90% of the year, whereas broad acre crops have one planting, or in some cases two or three plantings per year (ie lettuce) during the growing season.

The estimates for water use rely on the assumptions in Table 4. It should be noted that industry production is influenced by market demand and water use varies with the crop grown and stage of development, creating some variability in water use. The ABS figures used for area of production and water use (Table 1) also have some uncertainty (10-20%). Combined, the uncertainty could be + or – 40% and the data presented should be considered as averages with the associated error.

**Table 2:** Advantages and efficiencies of greenhouse and field production

Crop	Tomatoes	Capsicum	Cucumber	Lettuce	Cut flowers <sup>A</sup>
Greenhouse (kg/m <sup>2</sup> )	76	30	100	70	95
Field (kg/m <sup>2</sup> )	18	12	20	21	5
Efficiency gains %	422	250	500	333	1900

Sources: Smith 2005.

<sup>A</sup>Most flowers cannot be grown efficiently in the field, therefore efficiency gains are an indication only.

**Table 3:** Average area of greenhouse production and associated water use for Australian states and territories

State	Productions areas under greenhouse		Broadacre water use estimates (Figure 2)		Greenhouse water use estimates (DPI NSW <sup>C</sup> )		
	Vegetables	Cut flowers	Vegetables	Cut flowers	Vegetables	Lettuce	Cut flowers
	(Ha) <sup>A</sup>	(Ha) <sup>B</sup>	(ML/yr)	(ML/yr)	(ML/yr)	(ML/yr)	(ML/yr)
NSW	500	488	2,450	2,391	14,500	495	17,686
Vic	250	1,454	1,225	7,124	7,250	248	52,704
Qld	30	778	147	3,814	870	30	28,217
SA	580	352	2,842	1,725	16,820	574	12,764
WA	21	925	103	4,534	609	21	33,546
TAS	10	65	49	319	290	10	2,360
NT	na	15	na	72	na	na	533
<b>Total</b>	<b>1,391</b>	<b>4,078</b>	<b>6,816</b>	<b>19,908</b>	<b>40,339</b>	<b>1,377</b>	<b>147,809</b>
	<b>Total</b>	<b>5,469</b>	<b>Total</b>	<b>26,724</b>		<b>Total</b>	<b>189,525</b>

<sup>A</sup> Smith 2005, <sup>B</sup> HAL 2004, <sup>C</sup> Pers comm.. Jeremy Badgery-Parker, NSW DPI.

Note: Precise information on greenhouse area and water use were difficult to find and these figures represent to the best of the industry's knowledge.

These figures use have been calculated using information from references and the assumptions summarized in Table 4.

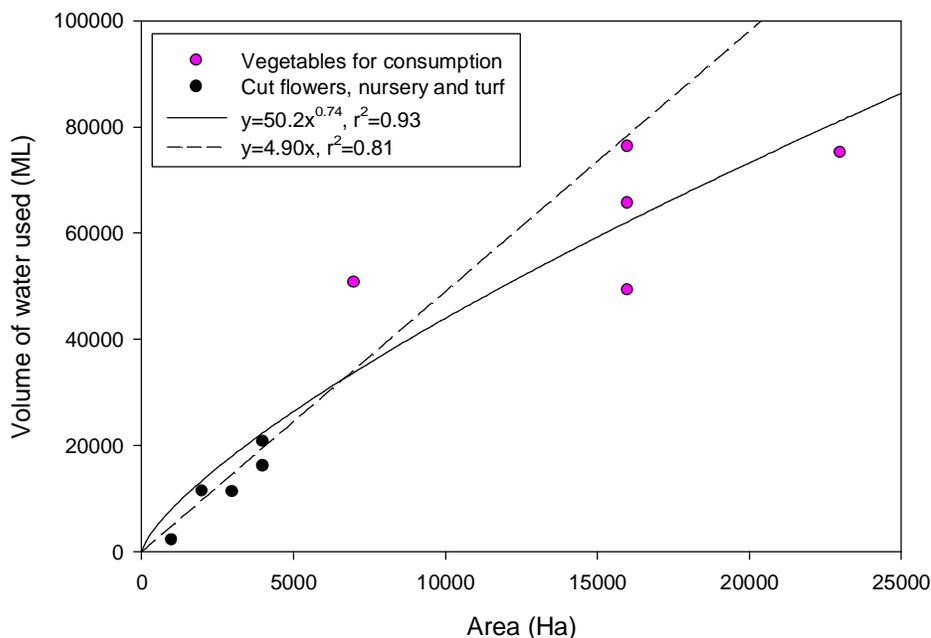
**Table 4:** Assumptions used for calculation of water use in greenhouse production in Australia

Crop	L/m <sup>2</sup> /day	Days grown/year	Portion of vegetable production
Vegetables	12.5	290	80%
Lettuce	1.5	330	20%
Cut flowers	12.5	290	

### Production

While there are no official statistics to clearly identify the hydroponic industry, it is estimated to have a farm gate value of \$600 million per annum. This equates to 20% of the total value of vegetable and cut flower production (HAL 2004).

Combining all sectors (retail, service providers, research, etc) the hydroponic industry contributes around \$1 billion to the national economy and employs over 10,000 people through out Australia (HAL 2004).



**Figure 2:** Areas of land compared to volume of water used in production of vegetables (compiled from ABS 2006b)

### 4.3 Wastewater quality and volumes from hydroponic systems

#### **Water quality levels suitable for use in hydroponic systems**

Plant nutrients (Table 5) are dissolved in the water used in hydroponics, and are mostly inorganic in nature and in an ionic form. Primary among the dissolved cations (positively-charged ions) are  $\text{Ca}^{2+}$  (calcium),  $\text{Mg}^{2+}$  (magnesium), and  $\text{K}^+$  (potassium); the major nutrient anions in nutrient solutions are  $\text{NO}_3^-$  (nitrate),  $\text{SO}_4^{2-}$  (sulfate), and  $\text{H}_2\text{PO}_4^-$  (phosphate).

Numerous 'recipes' for hydroponic solutions are available. Many use different combinations of chemicals to reach similar total final compositions.

**Table 5:** Essential mineral elements for higher plants

Classification	Elements
Macronutrients	N, P, S, K, Mg, Ca
Micronutrients	Fe, Mn, Zn, Cu, B, Mo, Cl, Ni
Micronutrients and 'beneficial' elements	Na, Si, Co (for some only)

Source: Marschner 1995

The general guidelines for hydroponic nutrient solutions are that they contain nutrients in amounts that are approximately proportional to plant tissue composition and that the total solution concentration does not damage the plant (Table 6).

Commonly-used chemicals for the macronutrients include potassium nitrate, calcium nitrate, potassium phosphate, and magnesium sulfate. Various micronutrients are typically added to hydroponic solutions to supply essential elements; among them are Fe (iron), Mn (manganese), Cu (copper), Zn (zinc), B (boron), Cl (chloride) and Ni

(nickel). Chelating agents are sometimes used to keep Fe soluble. Many variations of the nutrient solutions have been styled 'modified Hoagland solutions' and are widely used.

An example of what a modified Hoagland solution might contain is (Resh 2001):

- 0.4 mM  $\text{NH}_4\text{H}_2\text{PO}_4$ ;
- 2.4 mM  $\text{KNO}_3$ ;
- 1.6 mM  $\text{Ca}(\text{NO}_3)_2$ ;
- 0.8 mM  $\text{MgSO}_4$ ;
- 0.1 mM Fe as Fe-chelate;
- 0.023 mM B as  $\text{B}(\text{OH})_3$  [boric acid];
- 0.0045 mM Mn as  $\text{MnCl}_2$ ;
- 0.0003 mM Cu as  $\text{CuCl}_2$ ;
- 0.0015 mM Zn as  $\text{ZnCl}_2$ ;
- 0.0001 mM Mo as  $\text{MoO}_3$  or  $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24}$ ; and
- Cl as chlorides of Mn, Zn, and Cu (all concentrations in units of millimoles/litre)

### ***Volumes and quality of wastewater produced***

Most hydroponic systems in Australia have a wastewater stream that requires disposal by running to waste. Some have wastewater treatment systems or recycle wastewater. However, recycling systems also require unwanted salt removal from the feedwater to lower salinity and allow addition of sufficient nutrients to feed plants through the hydroponic system. This creates a waste stream usually concentrated with nutrients and unwanted salts. Transpiration of water through plants in the hydroponic system leads to water loss, and a lower amount of nutrient is removed by the plant. As water loss is greater than the total ions (salt) uptake in the hydroponic solution, the wastewater from the hydroponic system is concentrated in salts.

The loss of water can range from 50 to 80 percent which equates to a 2 to 5 times concentration factor of the ions (salts) in solution, respectively. However, there is also some ion removal through plant uptake of nutrients (ions or salts in solution in this case). As an average, it has been assumed that this might decrease concentration factors by 25% (ie 1.5 and 3.75). You cannot run hydroponic systems where all nutrients are removed as this may limit the nutrient supply to plants at the end of the hydroponic system. It should be noted that these figures and concentration factors vary considerable between crops grown, stage of growth, temperature, relative humidity, day length and hydroponic system used (Jones 1983; Resh 2001) and the data presented represent an average estimate for the industry.

Using these assumptions, the volumes of wastewater produced by the hydroponic industry are potentially large (Table 7) and require a system to manage this water from two perspectives:

- This water is currently used once and then returned to the natural water cycle (in most cases). Multiple passes before disposal would be a more water efficient system.
- Nutrients are wasted with the wastewater entering the environment where they may be detrimental.

This type of agricultural production system is also growing in Australia (See below – The future for the hydroponics industry). This growth will lead to increases in wastewater volumes in the future.

**Table 6 :General requirements for hydroponic nutrient solutions**

Parameter	Suitability Range	
PH	Suitable for all plants Possible phytotoxicity Possible precipitation of salts and consequent blockages	5.5 -7.0 <5.0 >7.5
Electrical conductivity (EC) dS/m	Sensitive crops Low tolerance Medium tolerance High tolerance Very high tolerance	0 - 0.7 0.7 -1.3 1.3 -3.0 3.0 – 5.0 5.0 – 8.0
Alkalinity (mg/L CaCO <sub>3</sub> )	Suitable for most plants Increasing problems Generally not suitable	<40 90 – 120 >125
Chloride (mg/L)	Suitable for most plants Tip burn on sensitive plants Not suitable	<70 <200 >400
Hardness (mg/L CaCO <sub>3</sub> )	Soft water Hard water Very hard water	<75 75 – 300 >300
Nitrates (mg/L)	Suitable for most plants Possible precipitation of salts and consequent blockages in irrigation system	<10 >25
Phosphorous (mg/L)	Limit for phosphorous sensitive plants Limit for plants already supplied with phosphorous	1 15
Potassium (mg/L)	Suitable for most plants	100 – 250
Sulphur (mg/L)	Suitable for most plants	60 -100
Magnesium (mg/L)	Suitable for most plants	20-50
Sodium (mg/L)	Suitable for most plants Unsuitable for many crops	<60 >120
Bicarbonate (mg/L)	Suitable for most plants Increasing problems with plant growth, staining and blockages in irrigation equipment Unsuitable	<90 90 -120 >500
Iron (mg/L)	No problems Iron bacteria may develop Staining and blockages in irrigation equipment Very difficult to treat	<0.2 0.3 – 1.5 1.5 – 4.0 >4.0
Copper (mg/L)	Suitable for most plants Becoming excessive for indoor irrigation systems Not recommended	<0.02 >0.05 >0.2
Fluoride (mg/L)	Maximum concentration for most plants	<1.0
Zinc (mg/L)	Suitable for most plants Not recommended	<0.2 >2.0
Manganese (mg/L)	Maximum concentration for irrigation Will clog irrigation equipment	0.5 >1.5
Boron (mg/L)	Suitable for most plants Not suitable for plants	<0.5 >2.0
Aluminium (mg/L)	Maximum concentration for most plants	5

Source: NSW DPI, Perscomm

**Table 7:** Estimates of the volumes of wastewater produced in Australia in all hydroponics systems (assumes all systems run-to-waste).

State	Vegetables (ML/yr)	Lettuce (ML/yr)	Cut flowers (ML/yr)	Total 50% loss (ML)	Vegetables (ML/yr)	Lettuce (ML/yr)	Cut flowers (ML/yr)	Total 80% loss (ML)
NSW	7,250	248	8,843	16,341	2,900	99	3,537	6,536
Vic	3,625	124	26,352	30,101	1,450	50	10,541	12,040
Qld	435	15	14,109	14,558	174	6	5,643	5,823
SA	8,410	287	6,382	15,079	3,364	115	2,553	6,032
WA	305	10	16,773	17,088	122	4	6,709	6,835
TAS	145	5	1,180	1,330	58	2	472	532
NT	na	na	266	266	na	na	107	107
<b>Total</b>	<b>20,170</b>	<b>689</b>	<b>73,905</b>	<b>94,763</b>	<b>8,068</b>	<b>275</b>	<b>29,562</b>	<b>37,905</b>

Notes: na – not available

1. 50% and 80% loss in the systems has been calculated to highlight the range of wastewater produced
2. Wastewater volumes may be lower for lettuce using NFT and there are some systems that don't run-to-waste.
3. These values do not include any pre salt removal required for poorer quality waters use as feed water.

If the quality of the wastewater from hydroponic systems is concentrated 1.25 to 3.75 times then wastewater will not be usable for the feed water because it will be:

- Too salty;
- Upset the balance of nutrients required for optimum crop growth;
- Contain plant pests (fungus, bacteria and viruses)

Even if it is put through a Reverse Osmosis (RO) system, this will produce a saline waste stream and possibly remove valuable nutrients.

#### 4.4 The future for the hydroponic industry

##### ***Soilless Horticulture***

For many horticulture crops grown in protected cropping systems, hydroponic, soilless culture systems will be the future method of cultivation. The DRW concept has the potential to ensure these agricultural systems are water efficient and have minimal impacts on their surrounding environment. Currently there are significant disposal problems with the nutrient rich and saline water collected at the end of the hydroponic process. There is also significant growth potential in this industry to supply global markets with high value products. The protected nature of these cropping systems is a key to enable overseas export. Overcoming this waste disposal problem will eliminate a significant hurdle for the industry.

##### ***Growth rate***

The industry is expanding at 4 – 6% per annum due mainly in part to consumer and market demand for premium quality produce all year round (Smith 2005). Supermarkets have encouraged expansion, particularly with hydroponically grown vegetables as these systems produce consistently high quality product and regular volumes through controlled environments. This allows better planning by retail outlets and more stable prices and 'smoothing out' of market price fluctuations associated with field grown produce which are subject to weather affects.

The increased cost of horticultural land in peri-urban areas has seen a land use change from open field grown farming to greenhouse/hydroponics, as growers

attempt to maximise their returns per unit area and make better use of resources such as water.

The added attraction of protective cropping is the ability to control the growing environment. The demand from the market place for consistent high quality produce is driving demand for produce that can only be grown in controlled environments.

Tomatoes are the largest area of vegetables grown in hydroponic greenhouse systems. Over the last few years there have been releases of new types and shapes of tomatoes which have received positive consumer response. All these new varieties can only be grown in greenhouses.

A similar situation will develop with capsicums (sweet peppers). This product has yet to take off as a greenhouse crop in Australia. However, they are widely grown in New Zealand in hydroponic greenhouses and exported to Australia where they attract premium prices over the field grown types.

#### **4.5 Costs associated with managing wastewater from hydroponic systems**

##### ***Today***

Some hydroponic systems are already adopting better practice for recycling and disposing of their wastewater. However, the costs associated with wastewater management are largely unquantified.

##### ***Future***

In Australia, an increase in the use of hydroponic production systems will increase water use and wastewater production from these systems. Increases in the cost of water will drive growers to be more efficient with their water and stricter environmental controls and charges for dumping wastewater will also begin to drive change.

The Netherlands is a major world greenhouse vegetable and cut flower producer. Legislation was introduced several years ago that ensures that all wastewater must be retained on growers' properties. This has meant that properties have to remove existing greenhouses and convert land over into holding areas for reuse.

Also open hydroponic systems, where excess water runs to waste, have been converted over to closed, recirculating systems. This works if there is excellent quality feed water. If not, a reverse osmosis system is required to treat the feed water which produces a brine waste stream (i.e. there will still be a wastewater problem).

In Australia, some local councils require wastewater from hydroponic farms to be treated to a level fit for release into waterways and this usually involves wetland treatment or irrigation to pasture.

There are also points for growers to adopt systems that minimise waste, are water efficient and completely close the loop in the waste cycle. These include becoming industry leaders and innovators, ready to embrace the environmental, social and economic benefits of using water efficiently, increasing the productivity of farms in water limited environments and to minimise environmental impacts.

#### 4.6 Potential value of nutrients in water recycled from treated sewage and hydroponic wastewater

The potential value of nutrients that can be saved using the DRW concept focuses on the nutrients N, P and K in this report. This is because significant amounts of the other major nutrients (S, Mg and Ca; Table 5) are often supplied in the feed water (especially if the feed water is not subject to RO) and therefore represent limited cost to growers, while N, P and K represent the major nutrient cost to growers.

There are approximately 2,800 growers cultivating vegetables and cut flowers using hydroponic farming systems in green houses (Table 8). The average farm size is small, because of the intense nature of the industry (ie large production from small areas nearly all year round).

The potential value of nutrients (NPK) in water recycled from treated sewage to the Australian hydroponic greenhouse industry is approximately \$12.5 million dollars. This is an average saving of \$4,400/grower/year on fertiliser costs (Table 8 and Table 9).

For the Australian hydroponic industry, the potential value of nutrients (NPK) in hydroponic wastewater is approximately \$1.2 million dollars, much lower than from treated sewage water (Table 11). This would potentially be a saving (on average) of \$400/grower/year.

**Table 8:** Estimate of grower numbers and area farmed with greenhouse hydroponic farming systems in Australia that grow vegetables and cut flowers.

State	No. of vegetables growers	Total area farmed in each state (Ha)	Average farm size (Ha)	No. of cut flower growers	Total area farmed in each state (Ha)	Average farm size (Ha)
NSW	680	500	0.7	360	488	1.4
Vic	200	250	1.3	220.8	1,454	6.6
QLD	80	30	0.4	296.8	778	2.6
SA	650	580	0.9	95.2	352	3.7
WA	30	21	0.7	128	925	7.2
Tas	25	10	0.4	32.8	65	2.0
NT				11.2	15	1.3
<b>Total</b>	<b>1665</b>	<b>1391</b>	<b>0.7<sup>A</sup></b>	<b>1144.8</b>	<b>4077.5</b>	<b>3.5<sup>A</sup></b>

<sup>A</sup> averages

<sup>B</sup> assumes 40% of all nurseries, cut flowers or cultivated, turf (ABS 2006b) are cut flower growers using hydroponic systems in greenhouses

The comparisons below suggests there may be direct economic benefits for treating water from treated sewage (Table 9), but limited value in capturing nutrients from hydroponic wastewater (Table 11). However, values for hydroponic wastewater do not consider the cost of environmentally friendly wastewater management and the value of the lost water resource. For example, if the value of the water that is run-to-waste is considered, this could range from \$2,600 to \$64,000 per grower per year (Table 12); depending on the price of water and percentage lost through evapotranspiration. Some growers already use potable water supplies for their hydroponic systems at a cost of 0.7 to \$1.20/KL. In these cases the DRW concept could produce economic benefits in the short term.

It is difficult to put a dollar value on the benefit to the environment by recycling the water and disposing of a waste stream appropriately. However, the impacts of salinity and eutrophication by saline and nutrient rich water have been shown to be devastating to many Australian environments.

If environmental protection agencies in Australia begin to regulate with much stricter controls on wastewater from hydroponic systems (as they have done in other industries already in Australia) like in the Netherlands, the cost associated with greenhouse production may increase to a stage where any form of waste management that provides a return will be beneficial to the industry.

If the cost of water rises in the future, the designer water concept should easily pay for itself (Table 12 and Table 13).

**Table 9:** Potential value of nutrients from water recycled from treated sewage to greenhouse hydroponic production in states and territories of Australia

Nut.	Hyd. (mg/L)	Average sewage effluent (mg/L) <sup>A</sup>	Nutrient cost <sup>A</sup> (\$/kg)	NSW	Vic	Qld	SA	WA	Tas	NT	Total for Australia (\$x1000)		
				Total water used hydroponic greenhouses (ML/yr) <sup>C</sup>									
				Value of NPK in water (\$x1000)									
				32,681	60,201	29,117	30,158	34,176	2,660	533			
N	15	15	1	490	903	437	452	513	40	8			
P	15	6	2.4	471	867	419	434	492	38	8			
K	150	40	0.9	1,207	2,223	1,075	1,114	1,262	98	20			
			<b>Total</b>	<b>2,168</b>	<b>3,993</b>	<b>1,931</b>	<b>2,000</b>	<b>2,267</b>	<b>176</b>	<b>35</b>	<b>12,570</b>		

Nut=nutrient, Hyd = hydroponic solution

<sup>A</sup>Data from Table 10

<sup>B</sup>2005 data.

<sup>C</sup>Table 3

## 5.0 Technology to recycle water

### ***Ability to manufacture specified water qualities***

High levels of salt in recycled water often prevents it's wider application for agricultural and horticultural irrigation. The current technology used to remove salt is reverse osmosis, which can remove most ions and molecules at a high energy and material cost. Some valuable nutrients including nitrogen, phosphorus, calcium, magnesium and sulphate are removed and discharged to the environment as waste. The significant cost of energy consumption, membrane cost and environment impact sometimes can not be justified, and so prevent wider use of reverse osmosis technology. It is desirable to produce a recycled water that contains nutrient components but without excessive levels of salt.

In the conventional arrangement, reverse osmosis treated water (permeate) is shandied with microfiltered water to produce water at the required total dissolved solids (TDS) concentration. The ratio of the two streams is dependent of the composition of the feed water and the TDS specification for the product water. The waste stream from the RO stage is a significant volume (~ 15-25% of the feed water) and contains brine and nutrients.

The DRW concept can minimise the salty waste produced from the desalination process, enhance the value of recycled water and minimise the loss of nutrients to the environment. DRW is a process that employs a multistage approach to separate

the larger divalent and trivalent ions and larger organic molecules by the less energy and cost demanding nanofiltration process. Permeate from the nanofiltration process is fed to the reverse osmosis membrane, and contains mainly salts and some smaller ions. By changing the various operating conditions, product water with designed nutrient and trace element concentrations can be obtained. This approach aims to achieve the ideal water quality for the proposed use (ie recycled water truly fit for purpose). An important component of the recycling process is disinfection of the water recycled from the hydroponic waste, as plant pathogens are a major concern for the hydroponics industry. The DRW may achieve this as part of the ultra filtration process or may require an additional disinfection step.

**Table 10:** Chemical constituents of sewage that could be used as a source of recycled water

Parameter	Symbol	Units	From reported median			
			Average	n	Minimum	Maximum
Total nitrogen	Ntot	mg/L	15.2	40	2.8	39.0
Ammonia	NH4	mg/L	8.4	11	0.1	34.0
Total phosphorus	Ptot	mg/L	5.9	40	0.0	12.0
pH		pH	7.9	31	6.2	9.8
Total dissolved salts	TDS	mg/L	675	25	145	1224
Electrical conductivity	EC	dS/m	1.3	15	0.2	2.9
Sodium adsorption ratio	SAR	(mmolc/L) <sup>0.5</sup>	6	15	3	12.2
Sodium	Na	mg/L	181	12	62.0	312.0
Calcium	Ca	mg/L	35	13	10	74.0
Magnesium	Mg	mg/L	19	13	6	40.0
Chloride	Cl	mg/L	135	10	9.3	340.0
Aluminium	Al	µg/L	227	10	11.0	665.0
Arsenic	As	µg/L	1.9	7	0.0	4.0
Barium	Ba	µg/L	9.7	5	1.0	37.5
Boron	B	µg/L	289	9	90	480
Cadmium	Cd	µg/L	0.3	8	0.1	0.5
Chromium	Cr	µg/L	9.4	9	1.0	21.0
Cobalt	Co	µg/L	0.7	5	0.4	1.3
Copper	Cu	µg/L	23.5	15	2.0	91.0
Cyanide	CN	µg/L	<1.0	4		
Iron	Fe	µg/L	722	11	30	4725
Lead	Pb	µg/L	5.4	10	1.0	20
Manganese	Mn	µg/L	35.2	7	19.0	69
Mercury	Hg	µg/L	0.1	6	0.1	0.2
Molybdenum	Mo	µg/L	9.8	5	1.0	21
Nickel	Ni	µg/L	7.0	14	2.0	20
Silver	Ag	µg/L	2.6	2	0.1	5.0
Zinc	Zn	µg/L	48	16	4.9	110

Source:NRMMC and EPHC 2005

Note: Possible recycled water sources surveyed from 40 sewage treatment plants across Australia.

n = number of samples for a particular parameter

**Table 11:** Potential value of nutrients from hydroponic wastewater to greenhouse hydroponic production in states and territories of Australia

Nut.	Hyd. (mg/L)	Average Hyd. waste (mg/L) <sup>A</sup>	Nutrient cost <sup>A</sup> (\$/kg)	NSW	Vic	Qld	SA	WA	Tas	NT	Total for Australia (\$x1000)		
				Total water used hydroponic greenhouses (ML/yr) <sup>C</sup>								Value of NPK in water (\$x1000)	
				6536	12040	5823	6032	6835	532	107			
N	15	5	1	33	60	29	30	34	3	1			
P	15	3	2.4	47	87	42	43	49	4	1			
K	150	20	0.9	121	222	108	111	126	10	2			
			<b>Total</b>	<b>200</b>	<b>369</b>	<b>179</b>	<b>185</b>	<b>210</b>	<b>16</b>	<b>3</b>	<b>1,162</b>		

Nut=nutrient, Hyd = hydroponic solution

<sup>A</sup>Data assumes active nutrient uptake is greater than concentration through evapotranspiration and that plants at the end of the nutrient system require sufficient nutrient to maximize yield. Further work is required to determine a more accurate figure for NPK values in hydroponic wastewaters.

<sup>B</sup>2005 data.

<sup>C</sup>Table 3

**Table 12:** Effects of water price on value of hydroponic wastewater recovered

State	Wastewater volumes if 50% loss (ML)	Water prices \$/KL				Wastewater volumes if 80% loss (ML)	Water prices \$/KL			
		0.2	0.5	1	2		0.2	0.5	1	2
		Water value (\$x1,000,000) <sup>B</sup>					Water value (\$x1,000,000) <sup>B</sup>			
NSW	16,341	3.1	7.8	15.5	31.0	6,536	1.2	3.1	6.2	12.4
Vic	30,101	5.7	14.3	28.6	57.2	12,040	2.3	5.7	11.4	22.9
Qld	14,558	2.8	6.9	13.8	27.7	5,823	1.1	2.8	5.5	11.1
SA	15,079	2.9	7.2	14.3	28.6	6,032	1.1	2.9	5.7	11.5
WA	17,088	3.2	8.1	16.2	32.5	6,835	1.3	3.2	6.5	13.0
TAS	1,330	0.3	0.6	1.3	2.5	532	0.1	0.3	0.5	1.0
NT	266	0.1	0.1	0.3	0.5	107	0.0	0.1	0.1	0.2
<b>Total</b>	<b>94,763</b>	<b>18</b>	<b>45</b>	<b>90</b>	<b>180</b>	<b>37,905</b>	<b>7</b>	<b>18</b>	<b>36</b>	<b>72</b>
		\$x1000/yr					\$x1000/yr			
Annual saving per grower		6.4	16.0	32.0	64.1		2.6	6.4	12.8	25.6

<sup>A</sup> taken from Table 7

<sup>B</sup> assumes a 95% recover of wastewater as per MF/NF/RO option Table 13.

### **Merit of the multiple staged water treatment process**

In the case of desalinating lightly brackish water at WTP, thermodynamic calculations indicate that the overall product water recovery with conventional reverse osmosis would be approximately 80%, and would be limited by calcium phosphate and calcium fluoride precipitation. However, the inclusion of the nanofiltration step would enable higher water recoveries in excess of 90-95%. In effect the volume of the waste stream would be reduced from 20% to less than 5% of the feed volume, ie more recycled water can be used for irrigation. By changing the various operating conditions such as flow rate, pressure and membrane type, product water with designed nutrient and trace element concentrations can be obtained.

Another option to achieve the same objective is to include a seeded precipitation step to remove the divalent and trivalent ions. The precipitated components (nutrients) will be returned to the product stream to produce DRW. Both approaches aim to achieve the ideal water quality for the proposed use in hydroponic plant production.

A small mobile pilot plant is necessary to demonstrate and test the idea, and to enable an assessment of its technical feasibility and economic viability. The pilot plant will be tested in the laboratory using recycled water from WTP, after which it will be transported to vegetable grower field sites where the feasibility of this process will be evaluated.

The need for desalinating water at WTP is well documented. Less well known is how to solve the issues of medium to high salt content present in the recycled water with minimal brine waste and maximum nutrient recovery. The concept of designer recycled water is a very innovative solution to this problem. It not only removes the salt but also provides an opportunity to generate a larger quantity of recycled water that contains valuable nutrients for vegetable irrigation. Membrane distillation of the brine stream may also be used to further increase water and nutrient recovery, with ammonia being recovered at high pH along with fresh water. A salt product from further salt recovery from the concentrated brine using membrane distillation or other method can be reused as additives for other agricultural or horticultural activities. It will provide the missing link in making a closed loop system with low environmental impacts.

The following table estimates the additional costs of including nanofiltration and interstage precipitation in the standard process configuration.

**Table 13:** Estimated cost comparison of three water reclamation processes

Water reclamation process	Unit Cost of water (\$/m <sup>3</sup> )	Water reclaimed (%)	Water to waste (%)	Cost of treated water (\$/ha)	Fertiliser cost (\$/ha)	Total cost water and fertiliser (\$/ha)
Conventional RO	0.4 – 0.45/m <sup>3</sup>	75 - 85	25 - 15	1000-1125	540	~1540-1670
Accelerated Seed Precipitation -MF/RO	0.5 – 0.55/m <sup>3</sup>	90-95%	5-10	1250-1375	270	~1520-1650
MF/NF/RO	0.6 – 0.65/m <sup>3</sup>	> 95%	< 5%	1500-1625	270	~1770-1895

Sources: Leslie, Stevens *et al.* 2005

The key assumption is that the real fertiliser value can be realised (ie. cost saving growers fertiliser) and that the price of water will increase across Australia in the near future. It should be noted that some growers already use potable water sources for hydroponic production systems, and in these scenarios, given the cost of the water reclamation process being considered (Table 13) the DRW concept should provide direct environmental and economic benefits to the hydroponic industry and indirect social benefits to work force that supports this industry.

## 6. Summary

As the hydroponic industry continues to develop in Australia, the industry will be expected to meet responsible environmental conditions. Developing sustainable systems using recycled water will go a long way to achieving this goal, with the added benefit of saving growers input costs such as fertiliser and water.

Unless good quality feed water can be located, all hydroponic systems will produce a salty waste at the start of the process and/or at the end of the production system. In Australia, the volume of the wastewater has been estimated to be high, ranging from 38,000 to 95,000 ML annually across Australia for all greenhouse production systems. A significant proportion of this waste stream is produced in Victoria (12,000 to 26,500 ML annually). These volumes of water could have significant environmental impacts and, if recycled, provide economic gains in purchasing water, particularly if water prices increase in the future.

Therefore, the challenge for the DRW process is two fold:

1. To develop a system that uses the water more efficiently and reduces the waste volume (ie. increases water recovery), and
2. To concentrate the waste after the DRW process so as to produce a marketable by-product.

The designer water concept has the potential to take this first step. If integrated with solar drying ponds for the low volume of saline waste (5%) produced, it will help develop the second step and a truly closed system. This system will limit any detrimental environmental impacts and ultimately provide economic benefits in the future as wastewater disposal is more tightly regulated, the cost of water increases and water availability reduces.

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## **Appendix 2:**

### **Accelerated seeded precipitation pretreatment of municipal wastewater to reduce scaling**

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#### **Abstract**

Membrane based treatment processes are very effective in removing salt from wastewater, but are hindered by calcium scale deposit formation. This study investigates the feasibility of removing calcium from treated sewage wastewater using accelerated seeded precipitation. The rate of calcium removal was measured during bench scale batch mode seeded precipitation experiments at pH 9.5 using various quantities of calcium carbonate as seed material. The results indicate that accelerated seeded precipitation may be a feasible option for the decrease of calcium in reverse osmosis concentrate streams during the desalination of treated sewage wastewater for irrigation purposes, promising decreased incidence of scaling and the option to control the sodium adsorption ration and nutritional properties of the desalted water. It was found that accelerated seeded precipitation of calcium from treated sewage wastewater was largely ineffective if carried out without pre-treatment of the wastewater. Evidence was presented that suggests that phosphate may be a major interfering substance for the seeded precipitation of calcium from this type of wastewater. A pH adjustment to 9.5 followed by a one-hour equilibration period was found to be an effective pre-treatment for the removal of interferences. Calcium carbonate seed addition at 10 g L<sup>-1</sup> to wastewater that had been pre-treated in this way was found to result in calcium precipitation from supersaturated level at 60 mg L<sup>-1</sup> to saturated level at 5 mg L<sup>-1</sup>. Approximately 90% reduction of the calcium level occurred 5 min after seed addition. A further 10% reduction was achieved 30 min after seed addition.

**Keywords:** calcium, interference, phosphate, effluent, water reuse, irrigation

## 1. Introduction

The world's growing human population is increasingly drawing upon our planet's fresh water resources. It is estimated that many capital cities in Australia will not have sufficient water supplies to meet their growing populations (Horticulture Australia Limited, 2006). Recycling and reuse of water is therefore becoming an increasingly important water management option.

Treated sewage effluent (commonly known as wastewater, recycled water or reclaimed water) is a water resource that has been under-utilized in Australia. About 94% of Melbourne's sewage ( $855 \times 10^3 \text{ m}^3 \text{ d}^{-1}$ ) is treated at two main treatment plants (Melbourne Water, 2007a). Less than 10% of this water resource is treated and utilized. The remainder is discharged to the environment (Horticulture Australia Limited, 2006).

Treated sewage plant wastewater contains considerable quantities of nutrients, making it an attractive option for its use in irrigation. It also, however, contains considerable quantities of salt. Approximately 45% of the salt in sewage that flows to one of Melbourne's sewage treatment plants comes from industry and about one-quarter comes from households. Salt in its various forms is widely used in manufacturing processes and is a by-product of many operations (Melbourne Water, 2007b).

The treated wastewater from Melbourne sewage treatment plants typically contains approximately  $1050 \text{ mg L}^{-1}$  total dissolved solids (TDS). Investigations have shown that the most appropriate and sustainable uses of recycled water require a salinity level of less than  $550 \text{ mg L}^{-1}$  TDS (Melbourne Water, 2007b). Therefore salinity reduction is required before sewage treatment plant effluent can be used in unrestricted irrigation applications.

Technologies for desalination include membrane processes, thermal distillation and ion exchange. Membrane and thermal distillation processes are the most commonly applied technologies in large desalination plants. Membrane based desalination processes are increasingly becoming accepted as the method of choice for a wide range of applications. Reverse osmosis (RO) for brackish water desalination is the most utilised method in Australia (Barron, 2006).

One of the major impediments to the widespread use of membrane based processes is the fouling of membranes, leading to higher energy requirements and irreparable damage to the membrane. This fouling can be caused by colloidal material (Lee et al. 2004), microorganisms such as bacteria (Park et al., 2005), organic material such as humic acids (Tang et al., 2007) or inorganic material such as mineral salt scale (Sheikholeslami, 2003).

Mineral salt scaling can occur when ions such as  $\text{Ca}^{2+}$ ,  $\text{Ba}^{2+}$ ,  $\text{CO}_3^{2-}$ ,  $\text{SO}_4^{2-}$ ,  $\text{F}^-$  and  $\text{PO}_4^{3-}$  in the membrane concentrate stream are concentrated above the solubility limit of sparingly soluble salts (e.g., calcium carbonate, calcium sulfate, calcium fluoride, calcium phosphate, barium sulfate). This scaling leads to permeate flux decline, lower water recoveries and shortening of membrane life (Rahardianto et al., 2006). Although membrane elements can be cleaned using a variety of chemicals, this cleaning may require interruption of the desalination process and generates secondary effluent for disposal.

The composition of sewage treatment plant wastewater is subject to seasonal and yearly variation. The average levels of calcium in monthly monitoring trials of

wastewater from one of Melbourne's sewage treatment plants has been reported to be approximately  $35 \text{ mg L}^{-1}$  (Southern Rural Water, 2006). This concentration would be expected to double in the concentrate stream of a membrane filtration process operated at 50% water recovery. Such an increase in calcium levels is expected to cause scaling at the membrane surface, leading to flux decline, higher power consumption and compaction of the membrane.

There are three main options to avoid or minimize the formation of scale: lowering the pH (for calcium carbonate or calcium phosphate scale), running the plant at lower water recoveries, and removing the calcium by seeded precipitation.

Treated wastewater from sewage treatment plants is often supersaturated with respect to calcium. However, supersaturation alone is not sufficient for commencement of precipitation in a solution. There must exist in the solution a number of seeds that act as centres of nucleation. Accelerated seeded precipitation involves the addition of nucleating site for precipitation of ions from this supersaturated solution. The rate of accelerated precipitation depends largely on the degree of supersaturation and the number of nucleating sites added to the solution.

The use of accelerated seed precipitation to remove the scaling ions from the first stage RO concentrate, before feed to the next stage RO, can not only decrease the incidence of calcium scaling during desalination, but also allow greater control over the composition of the recycled water. If the water is recycled for agricultural irrigation, for example, it is possible to return some or all of the removed calcium and other ions to the (low salt) recycled water, thereby improving the sodium adsorption ratio and its nutrient value.

One of the difficulties associated with the use of accelerated seed precipitation for reduction of calcium in wastewater is the potential for interference by substances such as organics and phosphates present in the wastewater. These substances can interfere with calcium carbonate precipitation mechanisms (Sawada, 1997) by a variety of mechanisms that are not fully understood (He et al., 1999), which may involve adsorption and/or co-precipitation of the interfering substance onto the calcium carbonate lattice (House and Donaldson, 1986; Sewada, 1997). Concentrations of orthophosphate as low as a few  $\mu\text{M}$  have been found to significantly retard the rate of calcium carbonate crystal growth in seeded solutions (Lin and Singer 2005, 2006).

For seeded precipitation of sparingly soluble salts that have a pH dependent solubility (e.g. calcium carbonate, calcium hydroxyapatite) it is often necessary to raise the pH of the wastewater. This increases the extent of precipitation due to the lower solubility of these salts at higher pH values, and increases the speed of precipitation due to the effective increase in the supersaturation of the solution.

In the current study, the feasibility of using seeded precipitation to lower the level of calcium in sewage treatment plant effluent is investigated. Treated sewage treatment plant (TSTP) wastewater was spiked with calcium to approximately  $60 \text{ mg L}^{-1}$  in order to simulate the increase in calcium concentration associated with membrane treatment. Due to the complex nature of this wastewater, the expected increase in concentration of the many other wastewater constituents was not simulated in this study.

## 2. Materials and Methods

Analytical reagent grade calcium carbonate (Ajax Chemicals) was used as supplied for all experiments involving calcium carbonate seed addition

One litre of TSTP was dosed with 500  $\mu\text{L}$  of 100  $\text{g L}^{-1}$  calcium (as calcium chloride) and 150  $\text{g L}^{-1}$  carbonate (as sodium carbonate), thereby increasing the calcium concentration from the 25 to 75  $\text{mg L}^{-1}$  (Sample No. 1) or 31 to 81  $\text{mg L}^{-1}$  (Sample No. 2), and increasing the carbonate levels from 84 to 159  $\text{mg L}^{-1}$  (Sample No. 1) or from 90 to 165  $\text{mg L}^{-1}$  (Sample No. 2).

The pH of the calcium-spiked solutions was increased to 9.5 by dropwise addition of 1 M NaOH in a stirred 1 L beaker. The precipitate formed during the pH adjustment period was not removed prior to calcium carbonate seed addition. The precipitation lowered the soluble calcium concentration in the solutions. The starting concentration of soluble calcium at pH 9.5 was found to be approximately 60  $\text{mg L}^{-1}$  (Sample No. 1) or 65  $\text{mg L}^{-1}$  (Sample No. 2).

Ten mL samples of the solution were taken before and at various times after addition of the calcium carbonate seed material and immediately filtered through 0.2  $\mu\text{m}$  membrane filter unit (Schleicher and Schuell). Experiments involving the use of wastewater that had been previously treated by calcium carbonate seed addition or pH equilibration alone were filtered through a glass fiber filter (Advatec) prior to use.

For experiments involving phosphate addition, 250 mL of the pre-treated wastewater was spiked with 460  $\mu\text{L}$  of 5  $\text{g L}^{-1}$  phosphorus solution (as  $\text{NaH}_2\text{PO}_4$ ) with constant stirring.

Calcium analysis was performed with a Varian Atomic Absorption Spectrophotometer using a nitrous oxide- acetylene flame. Phosphorus analyses were conducted using the Vanadomolybdophosphoric Acid Colorimetric Method (Method 4500-P C, APHA, 1998). Solutions used in the investigation of seeded precipitation without background interference were prepared by spiking deionised water to 55  $\text{mg L}^{-1}$  calcium (as calcium chloride) and 82.5  $\text{mg L}^{-1}$  carbonate (as sodium carbonate). The particle size of the calcium carbonate seed material was determined using a Coulter 130LS particle size analyser.

## 3. Results and Discussion

### 3.1 Characterization of TSTP wastewater samples

The chemical compositions of the two wastewater samples used in this study are shown in Table 1. The water samples have a mineral content that is typical of municipal effluent sourced from low TDS waters, and would be classed as only slightly brackish TDS < 1000  $\text{mg L}^{-1}$ . However, the water's alkalinity provides buffering capacity and creates the potential for alkaline scale formation as the recovery increases in the RO.

**Table 1:** Chemical composition of TSTP wastewater samples used in this study, all concentrations are in parts per million (mg L<sup>-1</sup>).

<i>Parameter</i>	Sample No. 1*	Sample No. 2*
Alkalinity, as CaCO <sub>3</sub>	140	150
Fluoride	2.2	2.1
Chloride	350	370
Sulphur, as sulphate	81	88
Calcium	25	31
Magnesium	21	23
Sodium	240	250
Potassium	23	25
Iron	< 0.02	< 0.02
Manganese	0.004	0.001
Aluminium	0.01	0.01
Barium	< 0.002	0.003
Chromium	0.004	0.004
Copper	0.017	0.014
Nickel	0.013	0.013
Lead	0.001	0.002
Zinc	0.004	0.017
Mercury, as Hg	< 0.0001	< 0.0001
Nitrate, as N	8.3	9.7
Nitrite, as N	0.007	0.005
Ammonia, as N	< 0.1	< 0.1
Phosphate, as P	6.1	9.0
Silica, total as SiO <sub>2</sub>	1.1	8.7

\* Samples were taken directly from the discharge point of a sewage treatment plant on two different days approximately one week apart

### **3.2 Comparison of seeded precipitation in wastewater and calcium solutions**

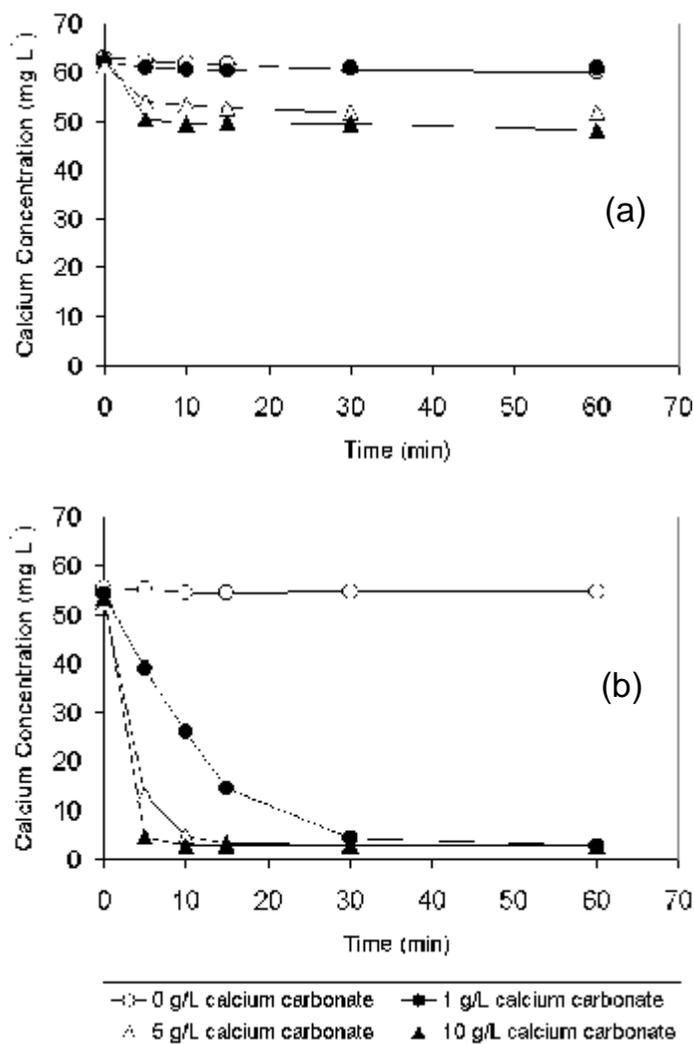
The potential for interference by substances such as organics and phosphates present in the wastewater has already been stated. The early parts of this research involved an assessment of accelerated seed precipitation treatment of the TSTP wastewater without prior treatment to remove interfering substances.

The calcium levels at various times after addition of various doses of calcium carbonate (Mean particle size =  $32 \pm 14 \mu\text{m}$ ,  $< 1 \mu\text{m} = 0\%$ ,  $< 10 \mu\text{m} = 3\%$ ,  $< 100 \mu\text{m} = 100\%$ ) to wastewater that had been spiked to approximately  $60 \text{ mg L}^{-1}$  soluble calcium ( $75 \text{ mg L}^{-1}$  before pH adjustment to 9.5) are shown in Fig. 1(a). The calcium level was increased by spiking to simulate the elevated calcium levels in the concentrate or reject stream of the RO membrane desalination process. Filtration of the raw wastewater prior to its use was not found to influence the calcium precipitation behaviour (results not shown), indicating that the suspended solids do not influence the calcium precipitation behaviour.

Direct application of accelerated seed precipitation of calcium from TSTP wastewater was found to be ineffective. A calcium reduction of only approximately 20% was achieved at the relatively high dose of  $10 \text{ g L}^{-1}$  calcium carbonate seed. Furthermore, the final calcium concentration achieved decreases with increasing calcium carbonate seed dose – a feature that is not consistent with an uninhibited seeded precipitation mechanism. In the absence of interferences the rate of calcium

removal but not the extent of calcium removal is expected to increase by increasing the number nucleation sites for precipitation.

The calcium reduction in TSTP wastewater (Fig. 1(a)) can be compared to that achieved for calcium chloride solutions (i.e., in the absence of interfering substances) in Fig. 1(b). In contrast to the results obtained for the TSTP wastewater (Fig. 1(a)), accelerated seed precipitation of calcium from deionised water that had been spiked with calcium chloride solution (i.e., without background interference) was found to be very effective (Fig. 1(b)). The calcium carbonate doses tested (1, 5 or 10 g L<sup>-1</sup>) were found to decrease the calcium levels to approximately 5 mg L<sup>-1</sup> within the first 30 min. At 10 g L<sup>-1</sup> calcium carbonate seed dose this level was achieved within the first 5 min.



**Figure 1:** Effect of calcium carbonate seed dose on calcium removal from: (a) TSTP wastewater Sample No. 1 at pH 9.5, calcium concentration before pH adjustment = 75 mg L<sup>-1</sup> and (b) calcium solution at pH 9.5.

### 3.3 Removal of interferences

The mechanism of inhibition of crystal growth by substances such as phosphate is not fully understood (He et al., 1999), but may involve adsorption and/or co-precipitation of the interfering substance as part of the calcite lattice (House, 1987; Sewada, 1997). Blockage of active crystal-growth sites by adsorbed phosphate has been widely accepted to be responsible for the reduced rate of calcite precipitation (Lin and Singer, 2006). This mechanism of interference involves the removal of the interfering substance from solution. Seed material addition to the water may, therefore, serve as a pre-treatment to remove the interfering substance. To test this, the treated TSTP wastewater used to generate the data in Fig.1 was dosed a second time with various quantities of seed material and the calcium concentration was measured. The results are shown in Table 2.

**Table 2:** Concentration of calcium ( $\text{mg L}^{-1}$ ) 60 min after repeated dosing with calcium carbonate at pH 9.5, TSTP Sample No. 1. Contact time for first dose was 60 min, the starting calcium concentrations are those at  $t = 60$  min in Fig. 1(a).

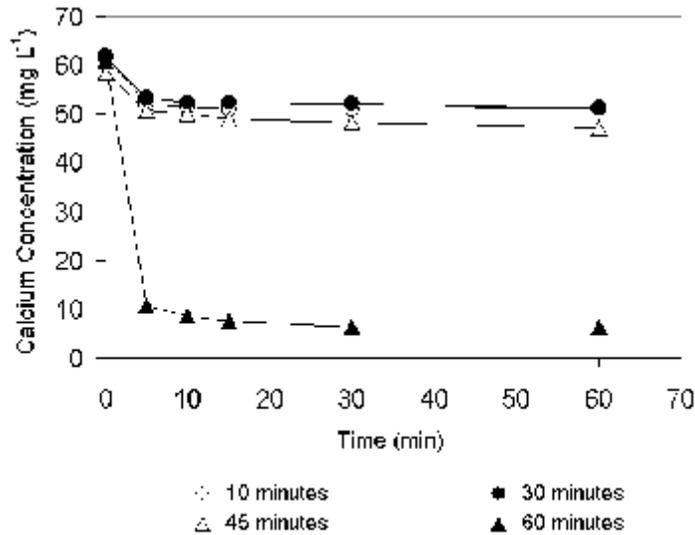
First $\text{CaCO}_3$ seed dose ( $\text{g L}^{-1}$ )	Second $\text{CaCO}_3$ seed dose ( $\text{g L}^{-1}$ )				
	0	1	5	10	15
0	-	-	47.2	6.3	-
1	-	50.3	41.6	6.5	4.2
5	53.3	51.2	39.1	5.6	5.7
10	51.8	49.8	40.2	5.4	6.5

The data show that, regardless of the size of the first dose, a second dose of  $10 \text{ g L}^{-1}$  is required for good calcium removal. The data also show the possibility that the pre-treatment does not necessarily need the addition of seed material. Simply adjusting the pH to 9.5, waiting for 1 h and then filtering is sufficient as pre-treatment for good removal to take place using  $10 \text{ g L}^{-1}$  calcium carbonate. This indicates that interfering substances present in the wastewater are removed from solution by precipitation during the 1-h pre-treatment period. The precipitation behaviour during the process will be further discussed in section 3.5.

### 3.4 Pre-treatment time requirements

The kinetics of calcium removal for wastewater that had been pre-treated by equilibrating for various time periods at pH 9.5 in the absence of seed material and subsequently dosed with calcium carbonate seed at  $10 \text{ g L}^{-1}$  is shown in Fig. 2.

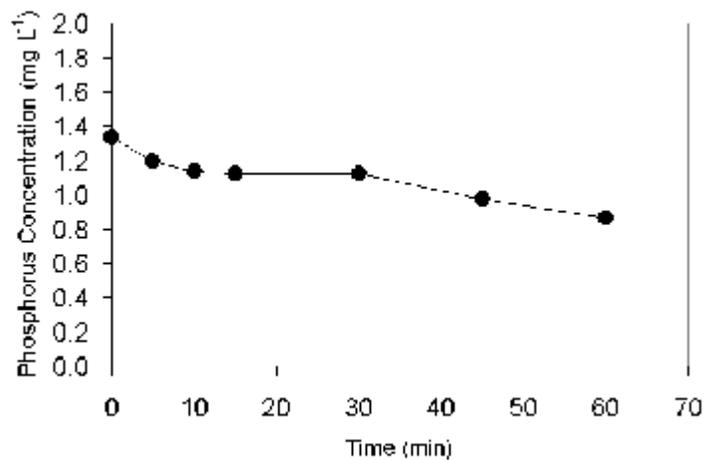
It can be seen that seeded precipitation after equilibration at pH 9.5 for periods of 45 min or less is not effective. The calcium reduction can be seen to be close to that observed without pre-treatment (see Fig. 1(a)). Seeded precipitation after 60 min equilibration at pH 9.5, however, was found to take place rapidly. The calcium concentration decreased to approximately  $11 \text{ mg L}^{-1}$  within 5 min, and to  $6.4 \text{ mg L}^{-1}$  within 30 min. This is in marked contrast to seeded precipitation using  $10 \text{ g L}^{-1}$  calcium carbonate without the 1 h equilibration pre-treatment period, where the minimum calcium concentration achieved was  $47 \text{ mg L}^{-1}$  (see Fig. 1(a)).



**Figure 2:** Seeded precipitation using  $10 \text{ g L}^{-1}$  calcium carbonate seed, TSTP Sample No. 1, pH equilibration in the absence of added seed material for various time periods prior to seed addition, contact time with added seed material = 60 min, filtration prior to seed addition.

### 3.5 Influence of phosphate

The identity of the interfering substance or substances in the wastewater under investigation is not known. Inspection of the wastewater composition (Table 1) reveals that phosphate levels are at levels that have been demonstrated to inhibit calcite formation in literature studies (Plant and House, 2002). It seems reasonable to suggest that the observed interferences in seeded precipitation seen for the TSTP wastewater may at least be partly due to phosphate. To investigate this, the levels of soluble phosphorus in the TSTP wastewater during the pH equilibration period were measured. The results are shown in Fig. 3.



**Figure3:** Phosphorus levels in filtered TSTP Sample No. 1 wastewater during pre-treatment period,  $0 \text{ g L}^{-1}$  calcium carbonate. (phosphorus concentration before pH adjustment was  $6.1 \text{ mg L}^{-1}$ ).

Adjusting the pH from the native pH of 7.8 to the seeded precipitation pH of 9.5 prior to the pre-treatment stage was found to decrease the soluble phosphorus concentration from the native concentration of  $6.1 \text{ mg L}^{-1}$  (see Table 1) to  $1.3 \text{ mg L}^{-1}$  ( $40 \text{ }\mu\text{M}$ ), indicating the formation of phosphate containing precipitate during pH adjustment to 9.5. Adjustment of the pH from the native pH to 9.5 prior to the pre-treatment stage was also found to decrease the soluble calcium concentration from approximately  $75$  to approximately  $60 \text{ mg L}^{-1}$ . This decrease in calcium concentration ( $0.375 \text{ mM}$ ) is approximately double the P concentration decrease ( $0.155 \text{ mM}$ ), suggesting that approximately half of the available Ca ions go towards the formation of a calcium phosphate salt and half go toward the formation of  $\text{CaCO}_3(\text{s})$  during pH increase from 7.8 to 9.5 prior to the pre-treatment and seeded precipitation stages of the experiment.

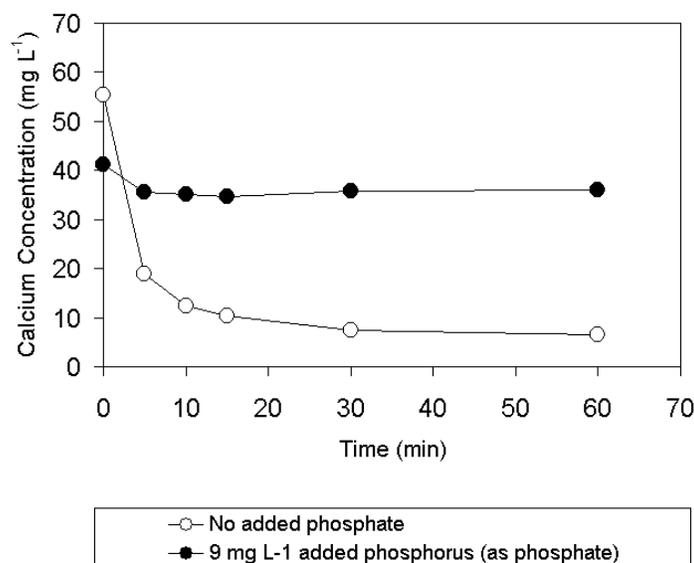
The identity of the calcium phosphate salt formed during pH adjustment from 7.8 to 9.5 is not known. Literature calcium phosphate speciation data (Moon et al., 2007) would suggest that, at the wastewater concentrations, this solid does not contain  $\text{CaHPO}_4$  but may contain other calcium phosphate species such as octacalcium phosphate ( $\text{Ca}_8\text{H}(\text{PO}_4)_6$ ) and hydroxyapatite ( $\text{Ca}_5(\text{PO}_4)_3\text{OH}$ ). Indeed, Moon et al. (2007) found that although a solution may be undersaturated with respect to  $\text{CaHPO}_4$ , the solid phosphate phases can tend to transform from  $\text{CaHPO}_4$  to  $\text{Ca}_4\text{H}(\text{PO}_4)_3$  to  $\text{Ca}_5(\text{PO}_4)_3\text{OH}$  with time.

The phosphorus concentration during the subsequent equilibration period at pH 9.5 (in the absence of added seed material) was found to further decrease from  $1.3$  to  $0.9 \text{ mg L}^{-1}$  (Fig. 3). This slow decrease may be attributed to further precipitation of calcium phosphate species and/or adsorption of  $\text{CaHPO}_4(\text{aq})$ , which exists in equilibrium with its solid forms, onto the freshly precipitated  $\text{CaCO}_3(\text{s})$  at pH 9.5. Calcium hydrogen phosphate ( $\text{CaHPO}_4(\text{aq})$ ) is believed to be the species that adsorbs on the calcite surface and inhibits calcite precipitation (Lin and Singer, 2006).

It is important to emphasise here that all solids were filtered out of the wastewater after pre-treatment (i.e., after equilibration at pH 9.5 for 1 h). Without this step in the procedure, the precipitated calcium phosphate would be expected to act as a large source of interfering calcium phosphate species, leading to inhibition of subsequent seeded precipitation of calcium carbonate.

Comparison of Figs. 2 and 3 suggests that a threshold phosphorus concentration exists for the two-stage process used here (i.e., pre-treatment by equilibration at pH 9.5, followed by seeded precipitation using  $10 \text{ g L}^{-1}$  calcium carbonate seed). Below this threshold, the phosphorus' influence as an interfering substance for seeded precipitation using  $10 \text{ g L}^{-1}$  calcium carbonate seed is negligible. This threshold is reached between 45 and 60 min into the pH 9.5 pre-treatment equilibration period. The data in Fig. 2 and Fig. 3 suggest that, at phosphorus concentrations below this threshold, the adsorbing phosphate species responsible for the interference is insufficient to block all the available nucleating sites on the calcium carbonate seed (at  $10 \text{ g L}^{-1}$ ), leaving sufficient active crystal growth sites for effective seeded precipitation. This explanation is supported by the data in Table 2 which show that a 1 h equilibration period at pH 9.5 (i.e., at  $0 \text{ g L}^{-1}$  first calcium carbonate dose) is insufficient to achieve the lower threshold concentration required for seeded precipitation with  $5 \text{ g L}^{-1}$  calcium carbonate seed dose. The lower seed dose of  $5 \text{ g L}^{-1}$  would be expected to require a longer pre-treatment time than 60 min to achieve a phosphorus concentration that is low enough to not block all the available nucleating sites on the calcium carbonate seed.

To further investigate the influence of phosphate levels on calcium removal by seeded precipitation, a sample of TSTP wastewater was equilibrated for 1 h at pH 9.5 as pre-treatment and subsequently filtered and split into two equal sub-samples for comparison. One sub-sample was left unaltered, the other was dosed with phosphate to  $9 \text{ mg L}^{-1} \text{ P}$  in order to bring the phosphate level back to the original TSTP wastewater level (i.e., before pH adjustment to 9.5). Both sub-samples were adjusted to pH 9.5 and then dosed with  $10 \text{ g L}^{-1}$  calcium carbonate. The levels of calcium at various times after calcium carbonate addition are shown in Fig. 4.



**Figure4:** Effect of phosphate addition, TSTP wastewater Sample No. 2, 1 h pre-equilibration at pH 9.5 in the presence of  $5 \text{ g L}^{-1}$  calcium carbonate, phosphorus concentration before pre-equilibration period:  $9 \text{ mg L}^{-1}$ ,  $10 \text{ g L}^{-1}$  second dose of calcium carbonate.

The initial calcium concentration was found to be lower in the phosphate-dosed sub-samples than the control (no added phosphate) sub-sample. This can be attributed to the formation of calcium phosphate precipitate as previously discussed. The formation of sparingly soluble calcium phosphate salts has been cited as one of the major problems associated with the RO treatment of treated sewage effluents (Greenberg and Semiat, 2005; Ning and Troyer, 2007), and the cause of membrane fouling at high phosphate antiscalant concentrations during RO treatment (Al-Shammiri et al., 2000).

It can be seen that in the absence of added phosphate, the calcium concentration rapidly decreased, as was the case in previous experiments with other wastewater samples, whereas in the presence of added phosphate, the calcium concentration remained largely unaltered. This is further evidence that suggests that the poor calcium removal seen in Fig. 1(a) and in the short equilibration time data in Fig. 2 is at least partly due to the presence of phosphate.

#### **4. Conclusions**

The results presented in this study indicate that seeded precipitation is a feasible option for the decrease of calcium in treated sewage treatment plant wastewater. Adjustment of the wastewater pH to 9.5 followed by a 1-h pre-treatment/ equilibration period prior to calcium carbonate seed addition at  $10 \text{ g L}^{-1}$  was found to result in calcium precipitation to its solubility limit. Calcium carbonate seed addition at  $10 \text{ g L}^{-1}$  to wastewater that had been pre-treated in this way was found to result in calcium precipitation from supersaturated level at  $60 \text{ mg L}^{-1}$  to saturated level at  $5 \text{ mg L}^{-1}$ . Approximately 90% reduction of the calcium level occurred 5 min after seed addition. A further 10% reduction was achieved 30 min after seed addition.

Evidence was presented that suggests that phosphate may be a major interfering substance for the seeded precipitation of calcium from this type of wastewater. It was found that a 1-h pre-treatment period was effective in the removal of interferences to the seeded precipitation of calcium from treated sewage treatment plant wastewater using  $10 \text{ g L}^{-1}$  calcium carbonate seed.

#### **Acknowledgements**

The authors thank the Smart Water Fund for funding this research.

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**Appendix 3:**

**Victoria University**

**Designer Water Membrane Systems  
Concept Design and Cost Estimation**

**Report**

**September 2008**

**Document No. 377997**



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**Revision Record**

<b>Re v.</b>	<b>Issue Date</b>	<b>Prepared</b>	<b>Checked</b>	<b>Approved</b>	<b>Comments</b>
0	11-Sep-08	AR	YT/JI	MC	First Issue
1	16-Sep-08	YT	MC	MC	Revision 1
2					
3					

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### **Introduction**

Victoria University has commissioned CH2M HILL to undertake a concept design and cost estimate for membrane treatment of secondary treated wastewater. The objective of this assignment is to undertake a concept design, cost estimation, and preparation of a report for various membrane arrangements for the treatment of secondary effluent.

This report is a record of the work undertaken on this assignment, including:

- **Outline of basis of design and cost estimate;**
- **Concept design and pricing of five (5) membrane treatment options;**

The treatment processes to be investigated are Nanofiltration (NF) and Reverse Osmosis (RO). These filtration processes are intended to be used to produce a recycled water (or 'designer water') that will be subjected to a number of membrane filtration barriers to produce clean filtered water (herein referred to as permeate). Provision for NF concentrate blending to the RO permeate will also be built into the design to allow remineralization or other purposes.

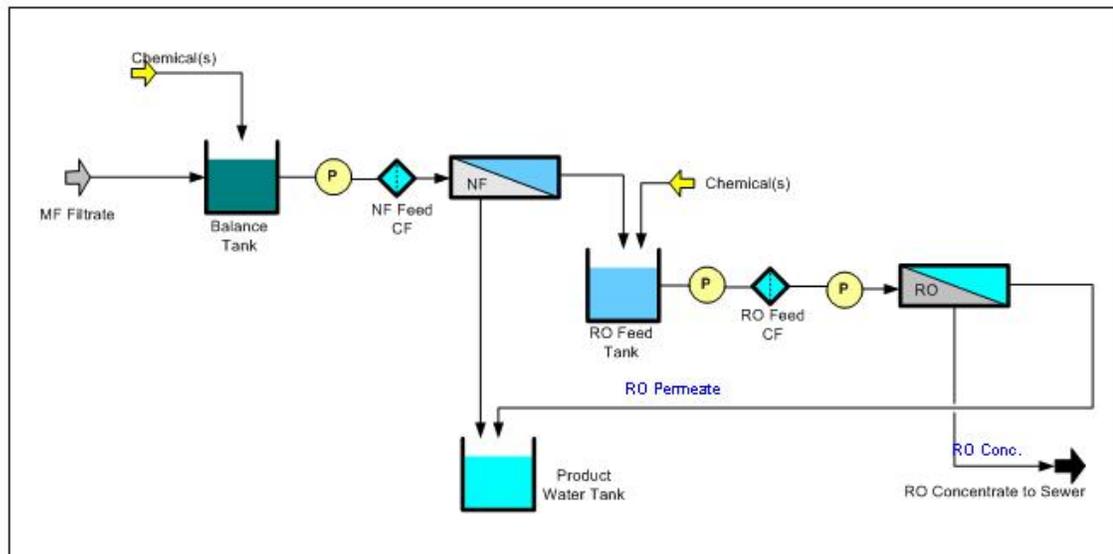
### **Basis of Design**

#### **Process Overview**

The five (5) treatment options, nominated for this study by Victoria University, are as follows:

- Case 1.* NF+RO system with 0 g/L Polyacrylic Acid (PAA) dose
- Case 2.* NF+RO system with 0.2 g/L PAA dose
- Case 3.* RO system of *Case 2* only (Feed : RO permeate → 23.7 : 76.3)
- Case 4.* NF+RO system with 0.7 g/L PAA dose
- Case 5.* RO system of *Case 4* (Feed : RO permeate → 30 : 70)

The general process flow arrangement is shown in Figure 2-1:



**Figure 0-1: General Process Flow Arrangement**

Influent or feed water to proposed treatment options are essentially pre-filtered secondary effluent from Western Treatment Plant (WTP). A micro-filtration (MF) system shall be installed upstream of NF and/or RO system to remove the suspended particulates in the feed water to avoid blockage or fouling of the NF/RO membranes.

The MF filtered effluent (referred to as MF filtrate) shall be stored in a balance tank where flow stabilization and conditioning chemicals dosing will occur. Conditioning chemicals are Polyacrylic Acid (PAA) and a provision for acid or antiscalant dosing if required. PAA functions to form complexes with divalent ions (e.g. calcium) to enhance the NF membrane salt rejection and performance.

From the balance tank the conditioned NF feed water will be pumped to the NF system. The NF permeate will be collected in the RO feed tank whilst the reject stream of the NF system (also referred to as concentrate stream) will be diverted to the product water tank for blending with RO permeate as final product water.

Subsequent to the NF process, the RO system will draw water from the RO feed tank where provision for antiscalant dosing is available to minimize membrane scaling if required. Depending on the RO high pressure pump capacity and selection, very often a booster pump may be required to fulfill the net positive suction head (NPSH) requirements of the high pressure pump and hence the RO feed pump is considered in this case to deliver the RO feed water to the membrane module via the high pressure pump.

RO permeate shall be fed to the product water tank, while the RO concentrate will be piped to the sewer.

5-micron cartridge filters are recommended prior to NF/RO feed which act as a guard filter to remove any suspended contaminant in the dosing chemicals or carried over in the feed water.

Refer to Appendix A for a detailed process flow diagram for each option.

**Plant Flow Capacity**

In order to create reasonable cost comparison between options, it is assumed that the plant capacity for cases 1, 2 and 4 (the NF/RO plants) shall be designed to produce 1.0ML/d (1,000m<sup>3</sup>/day) of product water.

Cases 3 and 5 are essentially control situations; looking at the RO requirements to treat the volume of NF permeate if it had come from cases 2 and 4.

**Feed Water Quality**

The assumed secondary treated effluent feedwater quality provided for the membrane system options is summarised in Table 0-1 which is based on sampling conducted in April 2007.

**Table 0-1: Water Quality Composition of Feedwater**

Parameter	Value (mg/litre)
Alkalinity, as CaCO <sub>3</sub>	150
Fluoride	2.1
Chloride	370
Sulphur, as sulphate	88
Calcium	31
Magnesium	23
Sodium	250
Potassium	25
Iron	< 0.02
Manganese	0.001
Aluminum	0.01
Barium	0.003
Chromium	0.004
Copper	0.014
Nickel	0.013
Lead	0.002
Zinc	0.017
Mercury, as Hg	< 0.0001
Nitrate, as N	9.7
Nitrite, as N	0.005
Ammonia, as N	< 0.1
Phosphate, as P	9.0
Silica, total as SiO <sub>2</sub>	8.7
pH (unit)	7.5 – 8.0
Temperature (°C)	15 - 20

**Basis and Assumptions**

The nominated treatment arrangements have been under bench scale pilot testing at Victoria University for a number of months. Subsequently, the experiment and modelling results from this pilot testing have formed the minimum requirements and assumptions that have been considered in designing the treatment options, as follows:

1. Membrane Selection

Koch’s SR2 and FilmTec’s BWRO-2540 were chosen during the pilot program at the Victoria University and therefore the proposed design is based on the same system except that the modules are commercially scaled. Koch SR2-400 and FilmTec’s BW30-400 are proposed for NF and RO, respectively. Both are 8-inch diameter by 40-inch nominal length modules with 400 ft<sup>2</sup> active membrane area.

2. As agreed, the FilmTec’s ROSA (Reverse Osmosis System Analysis) design software was utilized to size the proposed NF and RO systems instead of using the SR2 model (which is used for a different membrane manufacturer). Based on the experimental results Victoria University has advised that the SR2 model is likely to show better performance. Refer to Appendix C for comparisons.

3. System Recovery and Flux

The overall system recoveries and fluxes specified by Victoria University are as showed in Table 0-2.

**Table 0-2: Suggested NF & RO System Recoveries & Fluxes**

	Case 1	Case 2	Case 3	Case 4	Case 5
NF system flux (lmh)*	17.5 ± 5	24.0 ± 5	Not Applicable	18.0 ± 5	Not Applicable
RO system flux (lmh)*	23.5 ± 5	17.6 ± 5	17.6 ± 5	14.4 ± 5	14.4 ± 5
NF system recovery (%)	89.3	79.5	Not Applicable	71.3	Not Applicable
RO system recovery (%)	51.0	83.2	65.7	94.2	65.7

\* lmh = litre/m<sup>2</sup>/hour

4. The RO/NF projection is based on the minimum feed water temperature of 15 degree Celsius and assumed fouling factor of 0.85 which derived the maximum system feed pressure and power consumption. Victoria University shall review the above assumptions against the historical experimental data and membrane fouling conditions.

Refer to Appendix B for ROSA projections for each option.

5. The systems were designed to mimic bench scale pilot testing conditions and in some cases parameters used exceed the membrane vendor or system integrators recommended conditions. Vendors or system integrators have

specified that membrane life and suitable system performance may not be achieved under this situation.

6. As suggested by Victoria University the following are assumed during system design.
  - a. NF element recoveries shall be no greater than 15%
  - b. Permeate flow rate shall be no greater than 10% of vendor specified maximum flow rate per element.
  - c. Concentrate flow rate shall be no less than 60% of vendor specified minimum flow rate per element.
7. It is assumed that the concentrate stream of the above systems, as well as the cleaning wastewater, shall be piped to the sewer. Further treatment of the waste streams is not considered in the scope of this assignment.
8. The NF/RO system shall have automatic PLC control with pressure transducers, tank level switches, flow and conductivity meters, crossed safety system and alarms. A concentrate control valve will be included to allow adjustment to the required pressure by re-circulating the water.
9. The membrane Cleaning-In-Place (CIP) station is included in the system design, for options which involved both NF and RO system it is possible and more economical to share the CIP station with additional isolation valves and piping. The CIP station is generally designed in semi-automatic operation.

The CIP sequence would normally consist of several hold points that require manual initiation. These operating steps are essential and require operator input based on the extent of membrane fouling and impact on the associated upstream and downstream operations if any (e.g. if any peak product water requirements).

### **Process Schedules**

The overall process schedule consists of the following:

- Summary of ROSA projection
- Estimated Average Power Consumption
- Estimated Average Chemical Consumption
- Estimated Footprint

### ***Summary of ROSA Projections***

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Table 0-3 provides a summary of the ROSA projection outcomes for the nominated treatment options.



**Table 0-3: Summary of ROSA Projections**

Component	Parameter	Unit	Case 1	Case 2	Case 3 (RO only) Feed :ROP 23.7 : 76.3	Case 4	Case 5 (RO only) Feed :ROP 30 : 70
			<b>Value</b>				
<b>Plant Design Criteria</b>	Plant Product Water Flow Rate	m <sup>3</sup> /day	<b>1000</b>	<b>1000</b>	<b>790</b>	<b>1000</b>	<b>697</b>
<b>Nanofiltration (NF) Unit</b>	Overall Recovery	%	89.3	79.5		71.3	
	Feed Water Flow Rate	m <sup>3</sup> /day	1778.00	1154.15		1043.14	
	Permeate Flow Rate	m <sup>3</sup> /day	1587.75	917.55		743.76	
	Concentrate Flow Rate	m <sup>3</sup> /day	190.25	236.60		299	
	Number of Feed Pumps Required	No.	1	1		1	
	Feed Pump Pressure Required (+20% safety margin + 1bar losses across cartridge filter)	bar	7.8	9.4		8.1	
	Number of inter-stage booster Pumps Required	No.	1 (into stage 2)	N/A		N/A	
	Booster Pump Pressure Required	bar	3	N/A		N/A	
	Assumed Array		12x5 → 6x5 → 3x5	6x5 → 3x5		6x5 → 3x5	
	Number of Stages	No.	3	2		2	
	Number of Pressure Vessels (8" Diameter)	No.	21	9		9	

Component	Parameter	Unit	Case 1	Case 2	Case 3 (RO only) <i>Feed :ROP</i> 23.7 : 76.3	Case 4	Case 5 (RO only) <i>Feed :ROP</i> 30 : 70
		Value					
	Number of Elements	No.	105	45		45	
	Calculated Flux	Lmh	16.96	22.85		18.54	
	Flux specified by Vic. Uni.	Lmh	17.5	24		18	
<b>Reverse Osmosis (RO) Unit</b>	Overall Recovery	%	51.0	83.2	65.7	94.2	65.7
	Feed Water Flow Rate	m <sup>3</sup> /day	1587.75	917.55	914.49	743.76	743.76
	Permeate Flow Rate	m <sup>3</sup> /day	809.75	763.4	602.78	700.62	488.66
	Concentrate Flow Rate	m <sup>3</sup> /day	778	154.15	312	43	255
	Number of Feed Pumps Required	No.	1	1	1	1	1
	Feed Pump Pressure Required (+20% safety margin)	bar	17.5	14.9	15.2	12.0	13.9
	Assumed Array		6x6	4x7 → 2x7 → 1x7	4x6 → 2x6	4x7 → 2x7 → 1x7	4x6 → 2x6
	Number of Stages	No.	1	3	2	3	2
	Number of Pressure Vessels (8" Diameter)	No.	6	7	6	7	6
	Number of Elements	No.	36	49	36	49	36
	Calculated Flux	Lmh	25.2	17.46	18.77	16.04	15.22
	Flux specified by Vic. Uni.	Lmh	23.5	17.6	17.6	14.4	14.4

**Estimated Average Power Consumption**

**Table 0-4: Estimated average power consumption**

Parameter	Unit	Case 1	Case 2	Case 3 (RO only)	Case 4	Case 5 (RO only)
<b>NF System</b>						
Feed Water Flow Rate	m <sup>3</sup> /day	1,778	1,154		1,043	
Required Membrane Feed Pumping Pressure <sup>4</sup>	bar	7.8	9.4		8.1	
Assumed Overall Pump & Motor Efficiency	%	70%	70%	70%	70%	70%
Estimated Power Consumption	kWh/day	591	422	-	329	-
<b>RO System</b>						
Feed Water Flow Rate	m <sup>3</sup> /day	1,588	918	914	744	744
Required Membrane Feed Pumping Pressure <sup>4</sup>	bar	17.5	14.9	15.2	12.0	13.9
Assumed Overall Pump & Motor Efficiency	%	70%	70%	70%	70%	70%
Power Consumption	kWh/day	1,081	532	541	347	402
<b>Summary</b>						
15% Safety Factor (incl. of miscellaneous power)	kWh/day	251	143	81	101	60
Total Estimated Power Consumption	kWh/day	1,922	1,097	622	777	463
<b>Total Annual Power Usage<sup>1,3</sup></b>	<b>kWh/yr</b>	<b>692,036</b>	<b>394,938</b>	<b>223,884</b>	<b>279,842</b>	<b>166,513</b>
Estimated Power Cost <sup>2</sup>	\$/yr	\$ 83,040	\$ 47,390	\$ 26,870	\$ 33,580	\$ 19,980

Parameter	Unit	Case 1	Case 2	Case 3 (RO only)	Case 4	Case 5 (RO only)
Cost / ML of Product Water						
Daily Production (Final Product Water)	ML/d	1.000	1.000	0.790	1.000	0.697
Power Consumption/ ML of Final Product Water <sup>3</sup>	kWh/ML	1,922	1,097	788	778	663
<b>Estimated Power Cost<sup>2</sup></b>	<b>\$/ML</b>	<b>230.7</b>	<b>131.6</b>	<b>94.5</b>	<b>93.3</b>	<b>79.6</b>

<sup>1</sup> Assumed 360 days/year continuous operation

<sup>2</sup> Assumed AUD\$0.12/kWh

<sup>3</sup> The above exclude power consumption for up and downstream of treatment options, e.g. MF system, product water pump, compressed air system, product water pumping.

<sup>4</sup> Required membrane feed pumping pressure for each option is based on the ROSA projection results and additional 20% margin on frictional losses. NF membrane elements based on FilmTec's NF90-400.

**Estimated Average Chemical Consumption**

The ROSA projections have indicated solubility warnings for most of the treatment options. Indicators such as Langelier Saturation Index and Stiff & Davis Stability Index have shown values greater than zero on the concentrate streams, which suggested high scaling potential and therefore antiscalant may be required.

For costing purposes, it was assumed that a dose-rate of 5mg/L of antiscalant dose would be used for each option. In reality, antiscalant dosing will vary according to the water quality and operation regimes, and is typically dosed within the range 2 to 3 mg/L for systems operating within manufacturer’s recommended conditions.

Generally it is recommended to perform maintenance cleaning on the NF/RO membranes every 3 to 4 months even if they show no sign of fouling or scaling. This can become more frequent if water quality and membrane fouling/scaling figures dictate. The assumed chemical consumption quantities and costs for each of the cases is summarised in Table 2-5.

**Table 0-5: Estimated average chemical consumption**

Parameter	Unit	Case 1	Case 2	Case 3	Case 4	Case 5
NF Feed Flow	m <sup>3</sup> /day	1778	1154	NA	1043	NA
RO Feed Flow	m <sup>3</sup> /day			915		744
<b>Antiscalant</b>						
Antiscalant Dose Rate	mg/L	5	5	5	5	5
Chemical Conc.	%	100%	100%	100%	100%	100%
Assumed S.G.	-	1	1	1	1	1
Average Daily Consumption	L/d	8.89	5.77	4.58	5.22	3.72
Annual Consumption <sup>1</sup>	L/yr	3,200	2,077	1,647	1,877	1,339
	Unit Rate/L	\$5.50	\$5.50	\$5.50	\$5.50	\$5.50
	\$/yr	<b>\$17,602</b>	<b>\$11,425</b>	<b>\$9,059</b>	<b>\$10,326</b>	<b>\$7,366</b>
<b>PAA</b>						
PAA Dose Rate	g/L		0.2		0.7	
Average Daily Consumption	kg/d		230.8		730.1	
Annual Consumption <sup>1</sup>	ton/yr		83.1		262.8	
	Unit Rate/ton		\$1,728		\$1,728	
	\$/yr		<b>\$143,576</b>		<b>\$454,181</b>	
<b>Hydrochloric Acid (35%) for NF and RO CIP</b>						
Typical Cleaning Dose	%	0.2	0.2	0.2	0.2	0.2
Ave. Volume required per Pressure Vessel	L/PV	2.38	2.38	2.38	2.38	2.38
Total number of Pressure Vessels (NF+RO)	PV	27	16	6	16	6
Average volume required per CIP (NF+RO)	L/CIP	64.3	38.1	14.3	38.1	14.3

Parameter	Unit	Case 1	Case 2	Case 3	Case 4	Case 5
Assumed No. of CIP per year	CIP/yr	6	6	6	6	6
Annual Consumption	L/yr	386	229	86	229	86
	Unit Rate/L	\$1.10	\$1.10	\$1.10	\$1.10	\$1.10
	\$/yr	<b>\$424</b>	<b>\$251</b>	<b>\$94</b>	<b>\$251</b>	<b>\$94</b>
<b>EDTA (40%) for NF and RO CIP</b>						
Typical Cleaning Dose	%	1.0	1.0	1.0	1.0	1.0
Ave. Volume required per Pressure Vessel	L/clean	10.42	10.42	10.42	10.42	10.42
Total number of Pressure Vessels (NF+RO)	PV	27	16	6	16	6
Average volume required per CIP (NF+RO)	L/CIP	281.3	166.7	62.5	166.7	62.5
Assumed No. of CIP per year	CIP/yr	6	6	6	6	6
Annual Consumption	L/yr	1688	1000	375	1000	375
	Unit Rate/L	\$2.11	\$2.11	\$2.11	\$2.11	\$2.11
	\$/yr	<b>\$3,561</b>	<b>\$2,110</b>	<b>\$791</b>	<b>\$2,110</b>	<b>\$791</b>
<b>Sodium Hydroxide (50%) for NF and RO CIP</b>						
Typical Cleaning Dose	%	0.1	0.1	0.1	0.1	0.1
Ave. Volume required per Pressure Vessel	L/clean	0.83	0.83	0.83	0.83	0.83
Total number of Pressure Vessels (NF+RO)	PV	27	16	6	16	6
Average volume required per CIP (NF+RO)	L/CIP	22.5	13.3	5.0	13.3	5.0
Assumed No. of CIP per year	CIP/yr	6	6	6	6	6
Annual Consumption	L/yr	135	80	30	80	30
	Unit Rate/L	\$1.33	\$1.33	\$1.33	\$1.33	\$1.33
	\$/yr	<b>\$180</b>	<b>\$106</b>	<b>\$40</b>	<b>\$106</b>	<b>\$40</b>
<b>Estimated Total Chemical Consumption</b>	\$/yr	\$21,767	\$157,468	\$9,984	\$466,974	\$8,291
<b>Cost / ML of Product Water</b>						
Daily Production (Final Product Water)	ML/d	1.000	1.000	0.790	1.000	0.697
Annual Production <sup>1</sup> (Final Product Water)	ML/yr	360	360	284	360	251
Estimated Chemical Cost	\$/ML	<b>60.5</b>	<b>437.4</b>	<b>35.1</b>	<b>1,297.6</b>	<b>33.0</b>

<sup>1</sup> Assumed 360 days/year continuous operation

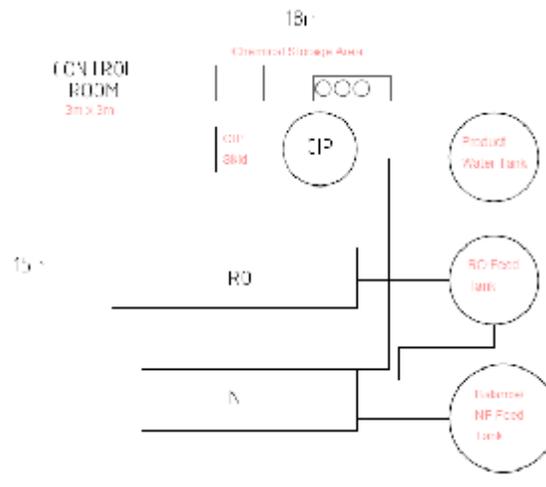
**Estimated Footprint**

Table 2-6 estimates the footprint area for each of the cases.

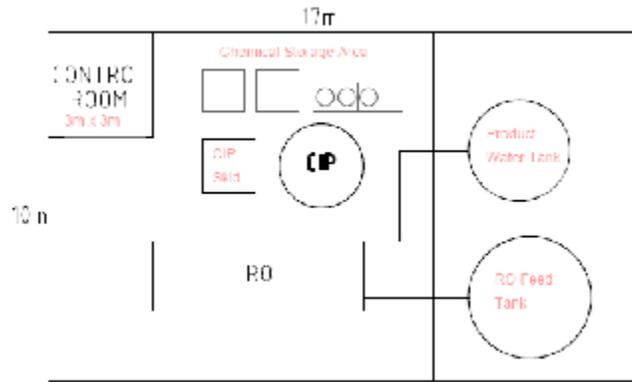
**Table 0-6: Estimated Footprint**

Treatment Options	Length x Width x Height
Case 1, 2 & 4	15 m x 18 m x 4.0m
Case 3, 5	10 m x 17 m x 4.0m

Please note that the Microfiltration and air compressor system for each case are excluded from the above footprint calculation. The proposed NF/RO feed tank and product water tanks are assumed to be approximately 10 to 20 m<sup>3</sup>. Chemical storages are assumed in portable chemical drums or IBC. Single duty train for each system is considered in this assignment as shown in following figures. If redundant train or 2-parallel duty trains are required, the estimated footprint would need to be revised.



**Figure 0-2: Estimated Footprint for Cases 1, 2 and 4**



**Figure 0-3: Estimated Footprint for Cases 3 and 5**

## **Cost Estimate**

### ***Basis of Estimate***

This section outlines the basis of the budgetary estimate for the membrane treatment options and includes the methodology for developing the cost estimates, including:

- **The development of first cut estimates;**
- **The assumptions used in calculating the prices;**
- **The methodology used in calculating the indirect cost estimates;**

The project team broke the project cost down into the following categories to identify an overall cost for each case, as follows:

- **Direct cost estimates** – these are primarily the direct costs for construction. A number of vendors were approached directly and requested to provide a cost estimate for the membrane treatment options. These estimates were utilised to provide initial, first cut estimates for the options.
- **Contingency estimate** – assumed to be 30%. This provides robustness in the concept design estimate and allows for modifications to existing equipment or the identification for minor additional equipment that may be recognised in functional and/or detailed design.
- **Commissioning cost estimates** – consists of training, O&M documentation, dry/wet commissioning, and process commissioning.
- **Project indirect cost estimates** – these are the non-construction costs in the delivery phase of the project including construction preliminaries & supervision, project management, design engineering and technical development, communications, HSE and operations liaison.
- **Land and building cost** – land and building costs are excluded in both CAPEX and OPEX calculations.

### ***Basis of Pricing***

Initially, the CH2M HILL proprietary design model CPES was intended to be used for cost estimation. Upon further investigation, this was not possible as the systems are below the unit's minimum capacity. As a result, the membrane treatment options were costed using vendor estimates. A number of add-ons were included in the final cost in order to account for additional construction and design costs. These costs are provided as  $\pm 30\%$  estimates and are likely to be more conservative than less. A number of assumptions were made for the pricing and these are outlined in Table 0-7.

**Table 0-7: Assumptions made for Pricing**

		Component	Assumption
<b>CAPEX</b>	<b>Margins</b>	Overhead	10%
		Profit	5%
		Mob/Bonds/Insurance	4%
	<b>Contingency</b>	Contingency	30%
	<b>Additional Project Costs</b>	Overall Site Work	5%
		Plant Computer System	2%
		Yard Electrical	5%
		Yard Piping	9%
	<b>Non-Construction Costs</b>	Engineering	9%
		Commissioning & Start-up	1.5%
<b>OPEX</b>	<b>Margins</b>	Repair & Maintenance	3% (of capital cost)
		Contingency	20% (of operating cost)
	<b>O&amp;M</b>	Power	\$0.12/kWh
	<b>Labour</b>	Plant Superintendent	\$65/hr
		Plant Operator	\$33/hr
	<b>Chemical</b>	Antiscalant	\$5.50/Litre
		Hydrochloric Acid	\$1.10/Litre
		EDTA	\$2.11/Litre
		Sodium Hydroxide	\$1.33/Litre
		PAA	\$1,728/dry tonne

**CAPEX**

Vendor estimates were gathered for 3 plants as follows:

- Plant 1: Case 1 – (NF + RO with 0 mg/L PAA)
- Plant 2: Case 2 – (NF + RO with 0.2 g/L PAA) and Case 4 – (NF + RO with 0.7 g/L PAA)
- Plant 3: Case 3 – (RO Only – Feed : RO permeate → 23.7 : 76.3) and Case 5 – (RO Only – Feed : RO permeate → 30 : 70)

Three (3) vendors were approached to provide cost estimates for each plant and the estimates provided are summarised in Table 0-8, Table 0-9, and Table 0-10.

**Table 0-8: Estimated Capital Cost for Plant 1**

Process Unit	Plant 1 Capital Cost (\$)		
	Veolia	GE	LCF
NF and RO Units (including CIP units)	\$900,000	\$960,000	\$750,000
Intermediate Tanks	\$35,000	Included	\$35,000
<b>Sub-Total</b>	<b>\$935,000</b>	<b>\$960,000</b>	<b>\$785,000</b>
Margins (including overhead, profit, and mobs/bonds/insurance)	\$177,650	\$182,400	\$149,150
Additional Project Costs (including plant computer system, yard electrical, yard piping)	\$151,725	\$155,782	\$127,384
Non-Construction Costs (including engineering, and commissioning and start-up)	\$98,175	\$100,800	\$82,425
Contingency	\$280,500	\$288,000	\$235,500
<b>Total CAPEX</b>	<b>\$1,643,050</b>	<b>\$1,686,982</b>	<b>\$1,379,459</b>

**Table 0-9: Estimated Capital Cost for Plant 2**

Process Unit	Plant 2 Capital Cost (\$)		
	Veolia	GE	LCF
NF and RO Units (including CIP units)	\$770,000	\$790,000	\$600,000
Chemical Dosing (PAA and antiscalant) and Intermediate Tanks	\$50,000	Included	\$35,000
<b>Sub-Total</b>	<b>\$820,000</b>	<b>\$790,000</b>	<b>\$635,000</b>
Margins (including overhead, profit, and mobs/bonds/insurance)	\$155,800	\$150,100	\$120,650
Additional Project Costs (including plant computer system, yard electrical, yard piping)	\$133,064	\$128,195	\$103,043
Non-Construction Costs (including engineering, and commissioning and start-up)	\$86,100	\$82,950	\$66,675
Contingency	\$246,000	\$237,000	\$190,500
<b>Total CAPEX</b>	<b>\$1,440,964</b>	<b>\$1,388,245</b>	<b>\$1,115,868</b>

**Table 0-10: Estimated Capital Cost for Plant 3**

Process Unit	Plant 3 Capital Cost (\$)		
	Veolia	GE	LCF
RO Unit (including CIP unit)	\$370,000	\$300,000	\$350,000
Intermediate Tanks	\$35,000	Included	\$35,000
<b>Sub-Total</b>	<b>\$405,000</b>	<b>\$300,000</b>	<b>\$385,000</b>
Margins (including overhead, profit, and mobs/bonds/insurance)	\$76,950	57,000	\$73,150
Additional Project Costs (including plant computer system, yard electrical, yard piping)	\$65,720	\$48,682	\$62,475
Non-Construction Costs (including engineering, and commissioning and start-up)	\$42,525	\$31,500	\$40,425
Contingency	\$121,500	\$90,000	\$115,500
<b>Total CAPEX</b>	<b>\$711,695</b>	<b>\$527,182</b>	<b>\$676,550</b>

**OPEX**

The annual operating costs estimated for each option are summarised in Table 0-11. Labour estimates allowed for one part-time plant operator and one part-time plant superintendent. Repair and maintenance costs were calculated as a percentage of the GE cost estimated, as this is considered to be the most accurate.

**Table 0-11: Estimated Annual Operating Costs for each Option**

Operating Expenditure (OPEX)	Plant 1	Plant 2		Plant 3	
	Case 1	Case 2	Case 4	Case 3	Case 5
Power Cost	\$83,040	\$47,390	\$33,580	\$26,870	\$19,980
Chemical Cost	\$21,767	\$157,468	\$466,974	\$9,984	\$8,291
Repair & Maintenance	\$50,609	\$41,647	\$41,647	\$15,815	\$15,815
Labour	\$89,180	\$89,180	\$89,180	\$89,180	\$89,180
Sub-Total	\$244,596	\$335,686	\$631,382	\$141,849	\$133,266
Contingency	\$48,919	\$67,137	\$126,276	\$28,370	\$26,653
<b>Total OPEX per annum</b>	<b>\$293,515</b>	<b>\$402,823</b>	<b>\$757,658</b>	<b>\$170,219</b>	<b>\$159,920</b>

**Summary**

This report includes a brief concept design and costing for 5 membrane arrangement cases for the treatment of secondary treated effluent from Western Treatment Plant to produce suitable recycled water quality. The intent of the report is to provide sufficient pricing information for Victoria University to make their own

recommendations in deciding the preferable membrane arrangement and CH2M HILL have not undertaken options assessment on this basis.

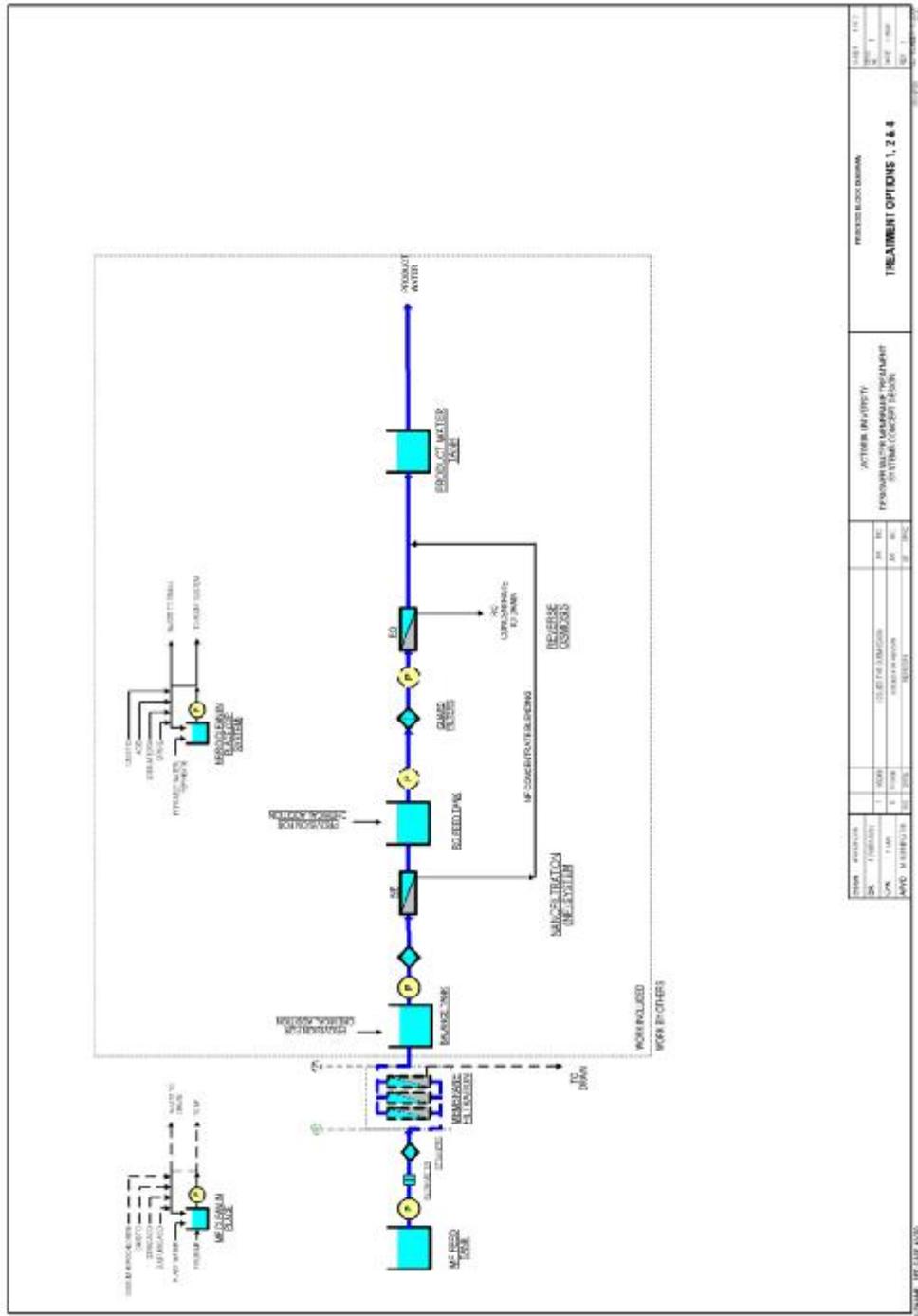
The five membrane arrangements were reduced to 3 plants for the purposes of capital cost estimation. This was due to similar capital requirements for certain cases. The cost estimate for each plant was developed to achieve a capacity of approximately 1.0ML/d (1,000m<sup>3</sup>/day) of product water.

In terms of capital expenditure costs the Plant 1 option (3-stage NF, 1-stage RO with no PAA dosing) is approximately \$1.686M and the Plant 2 option (2-stage NF, 2-stage RO with PAA dosing) is approximately \$1.388M. This compares with approximately \$0.527M for the Plant 3 option (3 stage RO control with no PAA dosing). The above estimates are based on the design assumptions outlined in the report with  $\pm 30\%$  accuracy.

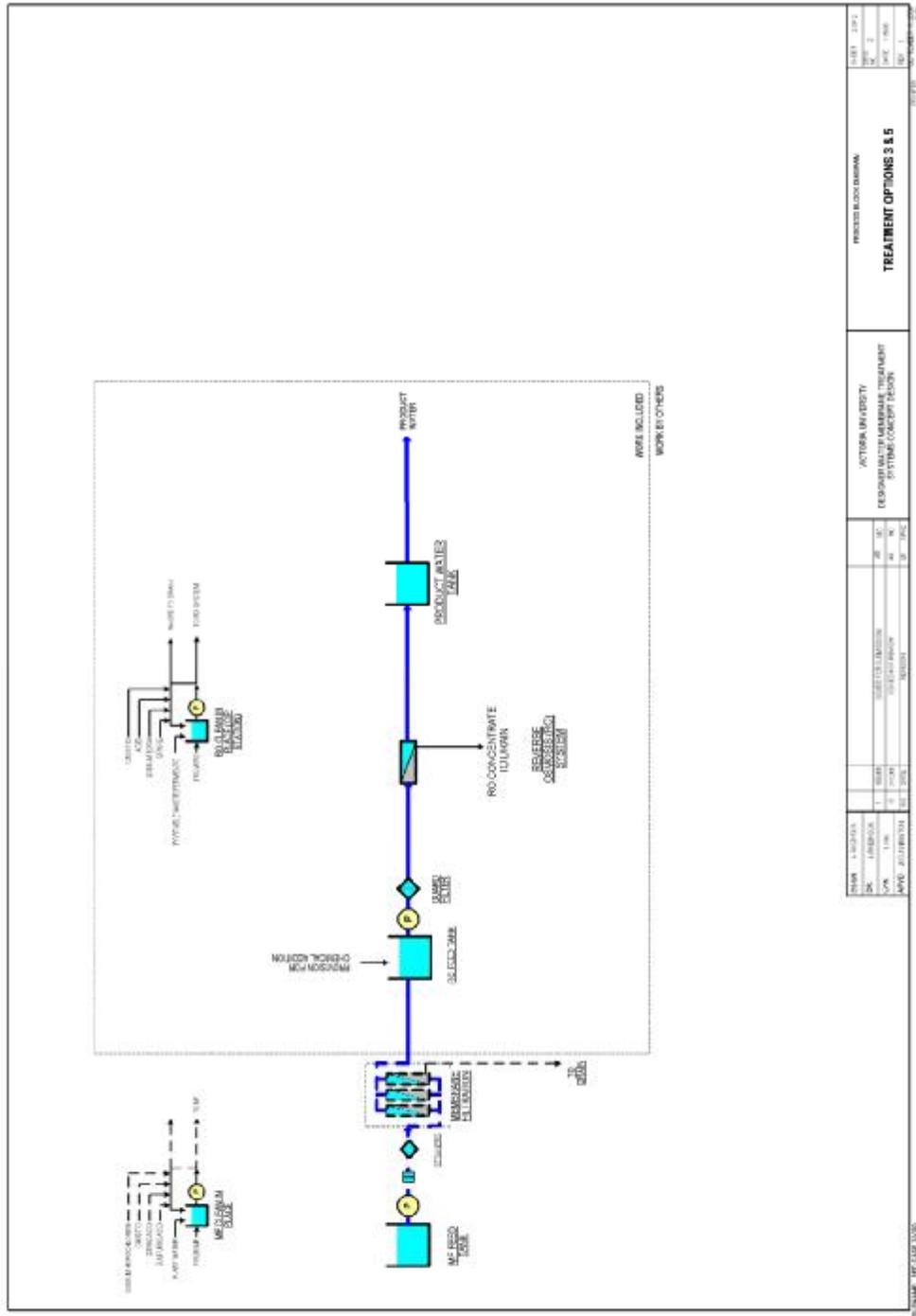


## Appendix A Process Flow Diagrams

Cases 1, 2 and 4:



Cases 3 and 5:



## Appendix B NF and RO Projections

**ROSA Detailed Report**

Page 1 of 5

Reverse Osmosis System Analysis for FULFILLMENT OF MEMBRANES  
 Project: 091008 Case 1 - Appendix B

ROSA v6.1.4 Config: B U238786\_03  
 Class: 2  
 7/9/2008

**Project Information:** Case 1 NF Flux: 19.0 l/m<sup>2</sup>/h / 0.5 l/m<sup>2</sup>/min NF Recovery: 89.5% RO Flux: 25.0 l/m<sup>2</sup>/h / 0.5 l/m<sup>2</sup>/min RO Recovery: 91%

**System Details - Pass 1**

Feed Flow (l/h) Stage 1	777.6 (1.74)	Total Feedwater Flow	687.6 (1.94)	Conductivity (µS/cm)	
Acid Water Flow (l/h) Stage 1	177.25 (1.21)	Pass 1 Recovery	89.51%	Feed	0.72 bar
Feed Pressure	6.02 bar	Feed Temperature	15.0 C	Concentrate	3.13 bar
Fouling Factor	0.85	Feed TDS	1120.21 (mg/l)	Average	3.02 bar
Chem. Dose	None	Number of Elements	105	Average NDF	3.96 bar
Total Active Area	1001.65 m <sup>2</sup>	Average Feed Flow	6.62 l/m <sup>2</sup>	Power	0.15 kW
Water Clean Index	Testory Ethanol (Membration) SDI < 3			Specific Energy	0.12 kWh/m <sup>3</sup>
System Recovery	91.26%			Conc. Factor (Pass 1)	3.00 (Pass 1)

Stage	Element	NFV (%)	Flow (l/h)	Feed Press (bar)	Retire Flow (l/h)	Conc Flow (mg/d)	Conc Press (bar)	Perme Flow (l/h)	Avg Flux (l/m <sup>2</sup> /h)	Perme Press (bar)	Boost Press (bar)	Perme TDS (mg/l)	
1	NF90-400	12	5	1777.91	6.18	0.00	330.74	1.53	921.38	17.21	2.00	0.00	191.96
2	NF90-400	6	5	856.74	5.18	0.00	406.72	4.58	470.51	16.84	0.00	0.00	201.70
3	RO90-400	3	3	405.22	3.21	0.00	190.13	6.70	216.20	16.16	0.00	2.00	102.00

Name	Pass Streams (mg/l on feed)										
	Feed	Adjusted Feed	Concentrate			Permeate			Total		
			Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3			
NT4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	29.49	29.49	15.09	75.62	121.23	13.12	21.37	29.21	29.21	18.41	
Na	288.72	288.80	572.38	1123.91	2316.31	21.22	19.89	103.88	124.64		
Mg	36.41	36.41	54.4	112.75	337.73	0.63	1.31	2.87	3.12		
Ca	33.28	33.28	72.31	130.67	217.81	0.81	1.72	3.73	3.73		
Si	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Fe	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
CO3	0.97	0.97	1.01	10.66	33.17	0.00	0.01	0.03	0.03		
HCO3	145.31	145.31	471.94	753.26	1438.54	0.00	20.20	43.42	17.27		
NO3	46.65	46.65	74.06	118.74	188.74	21.13	34.78	56.77	29.63		
Cl	401.41	401.41	798.85	1603.87	3261.14	33.60	69.75	147.18	52.17		
F	2.28	2.28	4.31	8.02	18.25	0.21	0.49	0.91	0.97		
SO4	95.17	95.17	190.35	412.52	875.66	1.14	2.46	5.36	2.10		
SiO2	8.12	8.12	16.45	33.81	70.38	0.17	0.78	1.70	0.67		
Thurs	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
CO2	3.17	3.17	1.85	8.31	14.79	3.22	6.45	9.81	6.20		
TDS	1120.67	1120.21	2230.72	4121.29	9010.02	104.96	201.70	402.70	172.91		
pH	7.70	7.70	7.90	8.00	7.09	6.51	6.75	6.84	6.67		

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**ROSA Detailed Report**

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Reverse Osmosis System Analysis for FILLMUTCHMCCultracres  
 Project: 091008 Case 1 - Appendix B

ROSA v6.1.4 Config: FB 0308786 - 11  
 Case: 1  
 7/3/2008

**Design Warnings - Pass 1**

**CAUTION:** The concentrate flow rate is less than the recommended minimum flow. Please change your system design to increase concentrate flow rates.  
 (P=45.0, KTF=1.0, Tm = 16.12=4°F)  
**WARNING:** Maximum element recovery has been exceeded. Please change your system design to reduce the element recoveries. (Product: NF90 400, Limit: 11.00%)

**Solubility Warnings - Pass 1**

Langelier Saturation Index > 0  
 Silt & Triox Solubility Index > 0  
 CaF2 (% Saturation) > 100%  
 Antiscalants may be required. Consult your antiscalant manufacturer for design and maximum allowable system recovery.

**Stage Details - Pass 1**

Stage	Element	Recovery	Perm Flow (m <sup>3</sup> /d)	1 Perm L/D (Gpd)	Feed Flow (GPD)	Feed TDS (mg/l)	Feed Press (bar)
Stage 1	1	0.12	18.29	70.92	110.10	1120.21	0.18
	2	0.13	18.77	85.41	129.87	1368.04	5.00
	3	0.13	19.25	100.91	149.64	1545.21	9.81
	4	0.14	19.90	127.15	179.75	1852.95	5.71
	5	0.15	20.48	158.01	219.88	1985.60	5.81
Stage 2	1	0.13	19.25	127.92	142.95	2210.73	0.18
	2	0.14	17.18	158.89	123.56	2594.47	5.01
	3	0.14	15.02	201.05	108.44	2916.14	4.57
	4	0.14	12.90	257.15	91.12	3361.75	4.72
	5	0.14	10.82	330.22	78.22	3870.25	4.86
Stage 3	1	0.13	20.44	215.27	115.41	4474.70	7.94
	2	0.13	17.21	308.83	114.97	5180.01	7.08
	3	0.14	14.97	413.23	97.70	6026.10	6.92
	4	0.14	11.79	563.94	83.83	6979.73	6.45
	5	0.13	9.15	741.24	72.40	7968.08	6.76

Element Flux reported by ROSA is calculated based on ACTIVE membrane area. **DISCLAIMER: NO WARRANTY, EXPRESSED OR IMPLIED, AND NO WARRANTY OF MERCHANTABILITY OR FITNESS IS GIVEN.** Neither Filtrac Corporation nor The Dow Chemical Company assume liability for results obtained or damages incurred from the application of this information. Filtrac Corporation and The Dow Chemical Company assume no liability, if as a result of customer use of the ROSA membrane design software, the customer should be sued for alleged infringement of any patent not owned or controlled by Filtrac Corporation or The Dow Chemical Company.

**ROSA Detailed Report**

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Reverse Osmosis System Analysis for FILMTEC™ Membranes  
 Project: 091008 Case 1 - Appendix B

ROSA v6.1.4 Config: FB 0308786 - 31  
 Case: 1  
 7/3/2008

**Project Information:** Case 1 NF Flux: 19.0 l/mh / 0.75 l/mh NF Recovery: 89.5% RO Flux: 25.2 l/mh / 0.75 l/mh RO Recovery: 21%

**System Details – Pass 2**

Feed Flow to Stage 1	1367.86 L/h	Flow to Permeate Flow	805.96 L/h	Concentrate Pressure	
Raw Water Flow to System	1367.86 L/h	Flow Recovery	59.01 %	Feed	2.11 bar
Feed Pressure	11.61 bar	Feed Temperature	15.0 C	Concentrate	0.25 bar
Fouling Factor	0.85	Feed TDS	177.94 mg/l	Average	0.17 bar
Chem. Dose	None	Number of Elements	36	Average TMP	13.18 bar
Chem. Addition Area	1337.52 L/h	Average Feed Flow	257.89 L/h	Flow	18.07 L/h
Water Clean Index: RO Permeate SDF < 1				Specific Energy	2.29 kWh/m <sup>3</sup>
System Recovery	43.26 %				

Stage	Element	SPW	STP	Feed Flow (m <sup>3</sup> /h)	Feed Press (bar)	Recirc Flow (m <sup>3</sup> /h)	Conc Flow (m <sup>3</sup> /h)	Conc Press (bar)	Perme Flow (m <sup>3</sup> /h)	Avg Flux (lmh)	Perme Press (bar)	Reject Press (bar)	Perme TDS (mg/l)
1	BW30-100	6	6	1367.89	11.27	0.00	777.92	11.42	809.94	25.23	0.00	0.00	3.67

Name	Feed	Adjusted Feed	Concentrate Stage 1	Permeate	
				Stage 1	Tube
NTS	0.00	0.00	0.00	0.00	0.00
K	19.47	19.47	26.66	1.01	1.01
Na	42.64	42.64	86.99	0.24	0.24
Mg	1.13	1.13	3.39	0.00	0.00
Ca	1.47	1.47	3.99	0.00	0.00
Si	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00
CO3	0.00	0.00	0.00	0.00	0.00
HCO3	17.27	17.27	37.00	0.48	0.48
NO3	29.65	29.65	26.80	1.67	1.67
Cl	29.17	29.17	120.18	0.29	0.29
F	0.37	0.37	0.75	0.00	0.00
SO4	3.10	3.10	4.39	0.00	0.00
SiO2	0.67	0.67	1.26	0.00	0.00
Turns	0.00	0.00	0.00	0.00	0.00
DO2	6.20	6.20	6.13	3.95	3.95
TDS	172.94	172.94	348.54	3.67	3.67
pH	6.67	6.67	6.96	5.70	5.70

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**ROSA Detailed Report**

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Reverse Osmosis System Analysis for FILMTEC™ Membranes  
 Project: 091008 Case 1 - Appendix B

ROSA v6.1.4 Config: DB 0338786 - 11  
 Case: 1  
 10/09/2008

**Design Warnings -- Pass 1**

-None-

**Solubility Warnings -- Pass 1**

-None-

**Stage Details -- Pass 1**

Stage	Element	Recovery	Feed Flow (m <sup>3</sup> /h)	Feed TDS (mg/L)	Feed Flow (GPM)	Feed TDS (mg/L)	Feed Press (bar)
1	0.09	23.75	2.53	267.61	172.94	14.25	
2	0.10	23.12	3.09	340.90	189.74	13.55	
3	0.10	22.60	3.70	211.78	205.60	13.12	
4	0.11	22.16	3.77	195.13	233.52	13.13	
5	0.13	21.81	4.23	173.02	262.99	13.55	
6	0.14	21.55	4.53	151.13	300.16	13.62	

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ROSA Detailed Report

Scaling Calculations

	Raw Water	Pass 1 Adjusted Feed	Pass 1 Concentrate	Pass 2 Concentrate
pH	7.70	7.70	7.99	6.96
Langelier Saturation Index	0.32	0.32	1.79	2.80
Stiff & Davis Stability Index	0.08	0.08	1.49	-1.32
Iron Strength (Moles)	0.00	0.00	0.17	0.01
CaCO <sub>3</sub> (mg/L)	1120.07	1120.21	8010.02	319.51
HCO <sub>3</sub> <sup>-</sup>	185.91	185.91	1558.58	95.12
CaCl <sub>2</sub>	2.17	2.17	11.79	6.21
CaSO <sub>4</sub>	0.02	0.02	33.77	0.02
CaSO <sub>4</sub> (% Saturation)	0.70	0.70	18.19	0.00
MgSO <sub>4</sub> (% Saturation)	0.00	0.00	0.00	0.00
MgSO <sub>4</sub> (% Saturation)	0.00	0.00	0.00	0.00
CaF <sub>2</sub> (% Saturation)	24.58	24.38	14071.95	0.32
SiO <sub>2</sub> (% Saturation)	7.73	7.73	61.58	1.09
Mg(OH) <sub>2</sub> (% Saturation)	0.00	0.00	0.08	0.00

Total Solids: 0.14 mg/L Na added to feed

**ROSA Detailed Report**

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Reverse Osmosis System Analysis for FILLMITE™ Membranes  
 Project: Case 2-07-07-08 (1)

ROSA v6.1.4 Config: B 0388786 22  
 Case: 2  
 7/8/2008

**Project Information:** Case 2 NF Flux: 24 lnh (experiment) / 7 lnh RT Recovery: 79.5% RO Flux: 17.6 lnh (experiment) / 7 lnh RT Recovery: 85.2%

**System Details – Pass 1**

Feed Flow (l/h Stage 1)	58.77 (1.6)	Feed Flow (m <sup>3</sup> /h)	0.7 (0.16)	Overall Recovery	
Acid Water Flow (l/h Stage 1)	1155.7 (12.8)	Pass 1 Recovery	79.49 %	Feed	0.71 lnh
Feed Pressure	0.8 bar	Feed Temperature	15.0 C	Concentrate	3.09 bar
Fouling Factor	0.85	Feed TDS	1138.70 (mg/l)	Average	1.88 bar
Chem. Dose	None	Number of Elements	45	Average NDF	5.18 bar
Feed Solution Area	670.70 m <sup>2</sup>	Average Feed Flow	28.66 lnh	Power	1.4 (kW)
Water Clean Index (Tertiary Effluent (Municipal)) SDI < 3				Specific Energy	0.7 (kWh/m <sup>3</sup> )
System Recovery	86.12 %			Conc. Recovery	92.0 (%)

Stage	Treatment	SPW (l/h)	Feed Flow (l/h)	Feed Press (bar)	Retire Flow (l/h)	Conc. Flow (mg/d)	Conc. Press (bar)	Perme Flow (l/h)	Avg Flux (lnh)	Perme Press (bar)	Boost Press (bar)	Perme TDS (mg/d)	
1	NF90-400	6	5	1155.77	7.52	0.00	117.64	0.61	606.13	23.78	2.00	0.00	19.98
2	NF90-400	3	5	517.64	6.77	0.00	336.61	1.49	281.68	21.01	0.00	0.00	196.84

Name	Feed	Adjusted Feed	Concentrate		Permeate		Total
			Stage 1	Stage 2	Stage 1	Stage 2	
			(mg/l as lnh)				
NaCl	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	101.47	101.47	307.56	109.49	16.77	33.86	33.01
Na	248.00	248.00	537.61	1125.04	16.47	39.34	23.48
Mg	25.11	25.11	55.31	119.91	0.19	1.10	0.60
Ca	30.7	30.71	66.68	144.74	0.53	1.30	0.77
Si	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>2</sub>	0.72	0.72	3.34	12.52	0.00	0.00	0.00
HCO <sub>3</sub>	187.51	187.51	399.28	839.17	3.36	20.01	11.80
NO <sub>3</sub>	47.94	47.94	83.68	141.54	18.86	37.12	23.84
Cl	494.03	494.03	845.95	1736.73	35.21	67.78	33.46
T	2.23	2.23	4.75	9.89	0.18	0.62	0.25
SO <sub>4</sub>	93.58	93.58	307.50	451.56	0.83	7.18	1.78
SO <sub>2</sub>	8.27	8.27	17.94	39.89	0.20	0.72	0.42
Boron	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>3</sub>	5.19	5.18	6.19	9.18	1.37	6.87	1.83
TDS	1136.97	1138.20	2425.71	5067.60	89.04	196.84	121.10
pH	7.70	7.70	7.91	8.00	8.11	6.69	6.53

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**ROSA Detailed Report**

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Reverse Osmosis System Analysis for FILLMITE™ Membranes  
 Project: Case 2-07-07-08 (1)

ROSA v6.1.4 Config: EB 0338786 22  
 Case: 2  
 7/8/2008

**Design Warnings - Pass 1**

**WARNING:** Maximum recommended element permeate flow rate has been exceeded. Please change your system design to reduce the element permeate flow rate. (Product: NF90 400, Limit: 61.54 GPD)

**WARNING:** Maximum element recovery has been exceeded. Please change your system design to reduce the element recovery. (Product: NF90 400, Limit: 13.00%)

**CAUTION:** The concentrate flow rate is less than the recommended minimum flow. Please change your system design to increase concentrate flow rates. (Product: NF90 400, Limit: 35.17 GPD)

**Solubility Warnings - Pass 1**

Tangher Solubility Index > 0  
 Silt & Davis Stability Index > 0  
 CWF2 (% Settlement) > 100%  
 Antiscalants may be required. Consult your antiscalant manufacturer for dosage and maximum allowable system recovery.

**Stage Details - Pass 1**

Stage	Element	Recovery	Perm Flow (m <sup>3</sup> /d)	Perm L/D2 (Gpd)	Feed Flow (Gpd)	Feed L/D2 (Gpd)	Feed Press (bar)
Stage 1	1	0.13	24.89	58.12	192.19	1138.20	7.52
	2	0.14	23.60	71.08	167.34	1099.08	7.33
	3	0.13	21.36	83.17	141.24	1091.63	7.04
	4	0.15	19.36	108.37	123.17	1076.70	6.86
	5	0.17	17.54	137.00	103.81	1059.51	6.70
Stage 2	1	0.13	23.89	122.19	192.19	2023.71	8.23
	2	0.14	21.33	153.49	148.69	2094.79	8.04
	3	0.13	18.77	195.20	127.16	2056.52	7.85
	4	0.15	16.17	252.17	108.36	2061.26	7.66
	5	0.17	13.56	332.16	92.45	2073.98	7.47

Permeate flux reported by ROSA is calculated based on ACTIVE membrane area. **DISCLAIMER: NO WARRANTY, EXPRESSED OR IMPLIED AND NO WARRANTY OF MERCHANTABILITY OR FITNESS FOR USE.** Neither FiltraTec Corporation nor The Dow Chemical Company assume liability for results obtained or damages incurred from the application of this information. FiltraTec Corporation and The Dow Chemical Company assume no liability, if as a result of customer's use of the ROSA membrane design software, the customer should be sued for alleged infringement of any patent not owned or controlled by the FiltraTec Corporation or The Dow Chemical Company.

**ROSA Detailed Report**

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Reverse Osmosis System Analysis for FILMTEC™ Membranes  
 Project: Case 2-07-07-08 (1)

ROSA v6.1.4 Config: DB 0338786 - 11  
 Case: 2  
 7/26/2008

**Project Information:** Case 2-07-07-08 (1) Flow: 24 mhd (experiment) / 7 mhd RO Flow, 79.5% RO Flux, 17.6 mhd (experiment) / 7 mhd RO Recovery, 85.2%

**System Details – Pass 2**

Feed Flow to Stage 1	5715.34	Feed Demand Flow	2887.64	Concentrate Pressure	
Raw Water Flow to System	11237.15	Pass 2 Recovery	93.21%	Feed	7.09 bar
Feed Pressure	12.28 bar	Feed Temperature	15.0 C	Concentrate	0.14 bar
Fouling Factor	0.55	Feed TDS	172.10 mg/l	Average	0.26 bar
Chem Doses	None	Number of Elements	40	Average NDB	9.77 bar
Feed Sulfonate	1692.84 NT	Average Feed Flow	727.19	Flux	24.85%
Water Clean Index: RO Permeate SDI < 1				Specific Energy	2.12 kWh/m <sup>3</sup>
System Recovery	85.12%				

Stage	Element	SPW (SD)	Feed Flow (m <sup>3</sup> /d)	Feed Press (bar)	Reconc Flow (m <sup>3</sup> /d)	Conc Flow (m <sup>3</sup> /d)	Conc Press (bar)	Perme Flow (m <sup>3</sup> /d)	Avg Flux (lmh)	Perme Press (bar)	Reconc Press (bar)	Perme TDS (mg/d)
1	BW30-100	4	917.15	12.01	0.00	116.25	10.30	170.90	18.16	1.10	0.00	3.90
2	BW30-400	5	446.55	9.95	0.00	235.91	8.55	210.34	16.85	0.50	0.00	7.05
3	BW30-100	1	225.91	7.88	0.00	151.91	5.50	81.99	13.15	0.00	0.00	13.87

Name	Feed	Adjusted Feed	Concentrate			Permeate			Total
			Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3	
			Press Streams (mg/L or bar)						
NT4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	22.01	22.01	13.97	31.16	121.98	1.19	2.26	4.22	1.83
Na	23.48	23.48	18.08	90.62	135.28	0.17	0.33	0.63	0.27
Mg	0.63	0.63	1.54	2.33	3.87	0.00	0.00	0.01	0.00
Ca	0.77	0.77	1.57	2.87	4.24	0.00	0.01	0.01	0.00
Si	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
HCO3H	11.99	11.99	24.40	45.96	70.17	0.46	0.52	0.66	0.50
NO3	21.84	21.84	47.70	86.63	128.19	1.81	3.42	6.58	2.80
Cl	17.46	17.46	76.73	144.68	221.30	0.75	0.50	1.75	0.41
F	0.23	0.23	0.52	0.88	1.48	0.00	0.00	0.01	0.00
SO4	1.28	1.28	2.69	4.96	7.60	0.00	0.01	0.01	0.00
SiO2	0.45	0.45	0.87	1.63	2.50	0.00	0.01	0.01	0.00
Brom	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2	5.89	5.89	5.84	5.86	5.88	0.17	0.60	5.66	5.89
TDS	122.10	122.10	217.19	461.20	700.19	2.90	7.05	13.57	5.84
pH	6.53	6.53	6.84	7.09	7.26	6.21	5.75	5.94	5.24

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**ROSA Detailed Report**

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Reverse Osmosis System Analysis for FILLMUTEC™ Membranes  
 Project: Case 2-07-07-08 (1)

ROSA v6.1.4 Config:FB 0398786 33  
 Case: 2  
 7/3/2008

**Design Warnings -- Pass 1**

-None-

**Solubility Warnings -- Pass 1**

-None-

**Stage Details -- Pass 2**

Stage	Element	Recovery	Perm Flow (m <sup>3</sup> /d)	Leak L/D (kg/d)	Feed Flow (kg/d)	Feed TDS (mg/l)	Feed Press (bar)
Stage 1	1	0.08	18.18	3.01	229.29	122.10	11.01
	2	0.08	17.97	3.05	211.16	132.35	11.68
	3	0.09	17.89	3.22	192.09	151.10	11.98
	4	0.09	16.68	3.32	176.50	157.75	11.08
	5	0.10	16.74	4.18	159.82	173.85	10.54
	6	0.11	16.96	3.61	142.45	193.21	10.52
	7	0.13	15.86	3.15	137.40	217.63	10.41
Stage 2	1	0.07	16.60	5.18	223.17	227.19	9.95
	2	0.08	16.82	5.66	206.52	266.67	9.51
	3	0.08	15.78	6.24	190.00	298.65	9.30
	4	0.09	14.97	6.91	175.00	313.68	9.03
	5	0.09	14.09	7.00	168.00	372.08	8.78
	6	0.10	14.08	8.68	142.00	370.78	8.57
	7	0.10	13.58	9.78	111.57	414.91	8.18
Stage 3	1	0.05	13.43	10.12	215.91	461.58	7.58
	2	0.05	12.78	11.39	222.43	488.84	7.50
	3	0.06	12.17	12.58	209.70	517.94	7.13
	4	0.05	11.62	13.86	197.51	549.09	6.82
	5	0.05	11.11	15.28	185.92	582.55	6.54
	6	0.05	10.60	16.82	175.80	618.62	6.27
	7	0.05	10.24	18.28	164.11	657.67	6.02

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ROSA Detailed Report

Scaling Calculations

	Raw Water	Pass 1 Adjusted Feed	Pass 1 Concentrate	Pass 2 Concentrate
pH	7.70	7.70	8.00	7.00
Langelier Saturation Index	0.39	0.39	1.20	2.05
Stiff & Davis Stability Index	0.02	0.02	1.04	-1.40
Tensile Strength (MPa)	0.00	0.00	0.00	0.01
CaCO <sub>3</sub> (mg/L)	1136.81	1136.20	3057.00	700.19
HCO <sub>3</sub> <sup>-</sup>	185.91	185.91	859.17	70.17
CaCl <sub>2</sub>	2.19	2.19	9.18	2.88
CaSO <sub>4</sub>	0.02	0.02	12.52	0.08
CaSO <sub>4</sub> (% Saturation)	0.60	0.60	8.14	0.01
MgSO <sub>4</sub> (% Saturation)	0.00	0.00	0.00	0.00
MgSO <sub>4</sub> (% Saturation)	0.00	0.00	0.00	0.00
CaF <sub>2</sub> (% Saturation)	19.97	19.97	1877.00	1.34
SiO <sub>2</sub> (% Saturation)	7.80	7.80	31.45	2.18
Mg(OH) <sub>2</sub> (% Saturation)	0.00	0.00	0.04	0.00

Total Solids: 1.89 mg/L (No added to feed)

**ROSA Detailed Report**

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Reverse Osmosis System Analysis for FILMTEC™ Membranes  
 Project: Case 3 09-07-08 (1)

ROSA v6.1.4 Config: DB 0308786 .22  
 Case: 3  
 7/10/2008

**Project Information:** Case 3 RO Recovery=82.0% RO Flux = 13.6 4/ 20lmh Same RO Feed Flow as Case 2

**System Details**

Feed Flow to Stage 1	91749 L/d	Total Permeate Flow	87573 L/d	Conductivity	
Raw Water Flow to System	91749 L/d	Stage 1 Recovery	82.0%	Feed	0.11 bar
Feed Pressure	12.07 bar	Feed Temperature	22.0 C	Concentrate	2.00 bar
Fouling Factor	0.85	Feed TDS	1145.00 mg/L	Average	1.96 hr
Chem. Dose	None	Number of Elements	16	Average NTRP	5.64 bar
Element Area/Area	133756 MP	Average Trans-Flux	18.75 L/m <sup>2</sup>	Trans-Flux	3.85 L/m <sup>2</sup>
Water Clean Index: Tertiary Effluent (Municipal) SDI = 3				Raw Water Energy	0.21 kWh/m <sup>3</sup>

Stage	Element	#PV	#El	Feed Flow (m <sup>3</sup> /d)	Feed Press (bar)	Reconc Flow (m <sup>3</sup> /d)	Conc Flow (m <sup>3</sup> /d)	Conc Press (bar)	Perm Flow (m <sup>3</sup> /d)	Avg Flux (lmh)	Trans Press (bar)	Trans Press (bar)	Perm TDS (mg/l)
1	BW20-100	4	6	91749	12.32	0.00	480.54	10.75	416.95	20.41	0.00	0.00	10.49
2	BW20-100	2	6	100.24	10.11	0.00	211.71	8.50	162.82	15.19	0.00	0.00	21.01

Name	Feed	Adjusted Feed	Concentrate		Permeate		
			(mg/L as CaCO <sub>3</sub> )		Stage 1	Stage 2	Total
			Stage 1	Stage 2			
NTs	0.00	0.70	0.00	0.00	0.03	0.00	0.00
K	101.47	101.47	191.71	289.96	2.22	3.23	3.08
Na	248.00	249.89	474.79	729.08	1.59	3.64	2.09
Mg	33.11	25.11	47.88	71.03	0.07	0.14	0.09
Ca	10.21	10.31	17.61	87.86	0.08	0.19	0.11
Sr	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>3</sub>	0.72	0.72	2.61	3.67	0.03	0.00	0.00
HCO <sub>3</sub>	181.91	181.91	930.19	799.74	1.37	3.01	1.81
NO <sub>3</sub>	47.91	17.91	88.96	132.33	2.83	0.60	3.87
Cl	291.02	391.02	730.23	1142.88	2.17	3.21	3.04
F	2.23	2.23	4.24	6.46	0.03	0.04	0.07
SO <sub>4</sub>	99.58	93.58	178.90	273.43	0.19	0.43	0.26
SR <sub>2</sub>	8.21	8.21	12.61	23.83	0.01	0.03	0.00
Brine	0.00	0.70	0.00	0.00	0.03	0.00	0.00
CO <sub>2</sub>	5.19	5.19	5.92	6.98	5.77	0.14	5.73
TDS	1196.81	1188.20	2162.48	3297.16	10.49	24.74	14.40
pH	7.70	7.70	7.88	7.96	5.69	5.66	5.79

Remarks: The reported by ROSA is calculated based on ACTIVE membrane area. **DISCLAIMER: NO WARRANTY, IMPROVED PERFORMANCE AND NO WARRANTY OF MERCHANTABILITY OR FITNESS FOR USE** Neither FilmTec Corporation nor the Dow Chemical Company assume liability for results obtained or damages incurred from the application of this information. FilmTec Corporation and The Dow Chemical Company assume no liability, if, as a result of customer's use of its ROSA membrane design software, the customer should be sued for alleged infringement or any patent not owned or controlled by the FilmTec Corporation nor the Dow Chemical Company.

**ROSA Detailed Report**

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Reverse Osmosis System Analysis for FILTRATECH Melbourne  
 Project: Case 3-09-07-08 (1)

ROSA v6.1.4 Config: EB 0338786 11  
 Case: 3  
 7/10/2008

**Design Warnings**

None

**Solubility Warnings**

Temperature Sulphur Index > 0  
 Salt & Doses Stability Index > 0  
 CaF<sub>2</sub> (% Saturation) > 100%  
 Anions may be required. Consult your anioniser manufacturer for dosing and maximum allowable system recovery

**Stage Details**

Stage 1	Element	Recovery	Perm Flow (m <sup>3</sup> /h)	1st Tr. TD <sub>50</sub> (mg/L)	Feed Flow (m <sup>3</sup> /h)	Feed TDS (mg/L)	Feed Press (bar)
	1	0.09	19.71	7.07	229.43	1158.20	11.41
	2	0.09	19.05	8.11	209.68	1294.17	11.97
	3	0.10	18.74	9.28	190.61	1467.89	12.56
	4	0.10	17.87	10.95	172.17	1613.32	13.18
	5	0.11	17.24	12.92	155.39	1887.19	13.82
	6	0.13	16.83	15.45	136.96	2498.97	14.91
Stage 2	Element	Recovery	Perm Flow (m <sup>3</sup> /h)	1st Tr. TD <sub>50</sub> (mg/L)	Feed Flow (m <sup>3</sup> /h)	Feed TDS (mg/L)	Feed Press (bar)
	1	0.07	15.75	17.19	210.23	2162.70	10.44
	2	0.07	14.95	20.21	224.53	2317.75	10.91
	3	0.07	14.18	23.04	208.23	2576.09	9.70
	4	0.07	13.42	26.25	195.39	2858.84	9.23
	5	0.07	12.68	30.01	181.97	3277.15	8.60
	6	0.07	11.91	34.29	169.30	3850.00	8.12

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ROSA Detailed Report

Scaling Calculations

	Raw water	Adjusted Feed	Concentrate
pH	7.70	7.70	7.96
Langelier Saturation Index	0.39	0.39	0.75
Stiff & Davis Stability Index	0.02	0.02	0.76
Tensile Strength (MPa)	0.03	0.03	0.06
CaCO <sub>3</sub> (mg/l)	1125.81	1138.20	1287.16
HCO <sub>3</sub> <sup>-</sup>	185.31	185.31	579.74
CaCl <sub>2</sub>	2.19	2.19	6.98
CaSO <sub>4</sub>	0.02	0.02	2.67
CaSO <sub>4</sub> (% Saturation)	0.60	0.60	7.03
MgSO <sub>4</sub> (% Saturation)	0.00	0.00	0.00
MgSO <sub>4</sub> (% Saturation)	0.00	0.00	0.00
CaF <sub>2</sub> (% Saturation)	10.97	10.97	487.25
SiO <sub>2</sub> (% Saturation)	7.83	7.83	31.31
Mg(OH) <sub>2</sub> (% Saturation)	0.00	0.00	0.02

Total Solids: 1.89 mg/l Na added to feed

**ROSA Detailed Report**

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Reverse Osmosis System Analysis for FILLMITE™ Membranes  
 Project: Case 4-07-07-08 (1)

ROSA v6.1.4 Config: DB 0338786 11  
 Case: 1  
 7/3/2008

**Project Information:** Case 4 NP Flux: 28 l/mh @ 2 l/mh NP Recovery: 91.3% RO Flux: 19.9 l/mh @ 2 l/mh RO Recovery: 91.2%

**System Details – Pass 1**

Feed Flow (l/h Stage 1)	643.94 (l/h)	Total Permeate Flow	544.5 (l/h)	Overall Recovery	
Acid Water Flow (l/h Stage 1)	1073.54 (l/h)	Pass 1 Recovery	71.31 %	Feed	0.85 bar
Feed Pressure	6.76 bar	Feed Temperature	15.0 C	Concentrate	2.61 bar
Fouling Factor	0.85	Feed TDS	1403.00 (mg/l)	Average	1.75 bar
Chem. Dose	None	Number of Elements	45	Average NDF	4.02 bar
Element Action Area	472.70 (m <sup>2</sup> )	Average Feed Flow	0.34 (l/h)	Power	3.5 (kW)
Water Clean Index (Tertiary Effluent (Municipal)) SDI < 3				Specific Energy	0.33 (kWh/L)
System Recovery	91.3 %			Conc. Recovery	92.0 %

Stage	Treatment	Flow (l/h)	Feed Flow (l/h)	Feed Press (bar)	Retire Flow (l/h)	Conc. Flow (mg/l)	Conc. Press (bar)	Perme. Flow (l/h)	Avg. Flux (l/mh)	Perme. Press (bar)	Boost Press (bar)	Perme. TDS (mg/l)
1	NP90-400	6	1913.54	6.81	0.00	114.14	1.59	629.00	19.19	1.50	0.00	121.28
2	NP90-400	3	514.14	1.71	0.00	395.36	4.37	214.79	16.06	0.00	0.00	348.48

Name	Feed	Adjusted Feed	Concentrate		Permeate		Total
			Stage 1	Stage 2	Stage 1	Stage 2	
			(mg/l as l/m <sup>3</sup> )				
NaCl	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	252.19	352.49	479.71	779.91	11.79	61.38	491.11
Na	241.07	341.07	471.13	780.00	17.65	37.71	211.44
Mg	20.85	20.85	11.97	71.35	0.34	0.70	0.10
Ca	28.55	28.55	57.48	98.01	0.46	0.99	0.61
Si	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>2</sub>	0.88	0.88	3.37	8.39	0.00	0.01	0.00
HCO <sub>3</sub>	212.10	212.10	119.60	691.52	13.38	28.52	17.70
NO <sub>3</sub>	56.78	56.78	90.75	127.14	33.79	40.04	23.48
Cl	466.91	466.90	910.99	1510.43	33.21	75.47	488.83
T	2.54	2.54	3.12	8.61	0.23	0.19	0.31
SO <sub>4</sub>	110.84	110.84	373.79	187.96	1.13	3.51	1.54
SO <sub>2</sub>	7.10	7.10	14.12	25.80	0.28	0.62	0.39
Boron	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO <sub>3</sub>	5.2	5.91	6.86	8.99	6.10	7.27	6.10
TDS	1402.98	1405.00	2713.06	4487.13	124.24	248.48	160.12
pH	7.70	7.70	7.88	7.96	6.59	6.81	6.67

Permeate Flow reported by ROSA is calculated based on ACTIVE membrane area. **DISCLAIMER: NO WARRANTY, EXPRESSED OR IMPLIED, AND NO WARRANTY OF MERCHANTABILITY OR FITNESS FOR USE.** CH2M HILL and its Corporation and The Dow Chemical Company assume liability for results obtained or damages incurred from the application of this information. CH2M HILL Corporation and The Dow Chemical Company assume no liability if, as a result of customer use of its ROSA membrane design software, the customer should be sued for alleged infringement of any patent not owned or controlled by the CH2M HILL Corporation or The Dow Chemical Company.

**ROSA Detailed Report**

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Reverse Osmosis System Analysis for FILMTEC™ Membranes  
 Project: Case 4-07-07-08 (1)

ROSA v6.1.4 Config: B U338786 11  
 Case: 1  
 7/3/2008

**Design Warnings - Pass 1**

**WARNING:** Maximum element recovery has been exceeded. Please change your system design to reduce the element recovery. (Product: NF90-400, Total: 14.00%)

**CAUTION:** The concentrate flow rate is less than the recommended minimum flow. Please change your system design to increase concentrate flow rates. (Product: NF90-400, Total: 0.00 L/min)

**Solubility Warnings - Pass 1**

Langelier Saturation Index > 0

SRP & Dose Stability Index > 0

CaF<sub>2</sub> (% Saturation) > 100%

Antiscalants may be required. Consult your antiscalant manufacturer for dosage and maximum allowable system recovery.

**Stage Details - Pass 1**

Stage	Element	Recovery	Perm Flow (m <sup>3</sup> /d)	Perm TDS (mg/l)	Feed Flow (m <sup>3</sup> /d)	Feed TDS (mg/l)	Feed Press (bar)
Stage 1	1	0.12	21.15	83.62	171.92	1402.00	6.11
	2	0.13	19.32	101.09	152.77	1385.54	6.15
	3	0.13	17.80	122.90	132.42	1300.27	5.89
	4	0.14	15.91	151.12	112.85	2054.86	5.82
	5	0.14	14.25	187.70	99.94	3357.59	5.70
Stage 2	1	0.11	18.20	188.92	171.78	2718.06	5.22
	2	0.11	16.22	205.60	153.09	3023.42	5.01
	3	0.10	14.20	251.29	138.81	3357.69	4.85
	4	0.10	12.20	300.27	122.61	3716.25	4.62
	5	0.10	10.22	349.25	110.31	4095.72	4.50

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**ROSA Detailed Report**

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Reverse Osmosis System Analysis for FILLMITE™ Membranes  
 Project: Case 4-07-07-08 (1)

ROSA v6.1.4 Config: B 0338786 11  
 Case: 1  
 7/3/2008

**Project Information:** Case 1 NP Flow: 28.0 m<sup>3</sup>/d 1.0 m<sup>3</sup>/d Recovery: 91.3% RO Flux: 15.0 l/m<sup>2</sup>/h 1.0 m<sup>3</sup>/d RO Recovery: 91.2%

**System Details – Part 2**

Feed Flow to Stage 1	74.16 m <sup>3</sup> /d	Feed Temperature	20.0 °C	Concentrate Pressure	
Raw Water Flow to System	179.51 L/S	Feed Recovery	91.32 %	Feed	2.10 bar
Feed Pressure	10.00 bar	Feed Temperature	15.0 °C	Concentrate	1.20 bar
Fouling Factor	0.85	Feed TDS	160.12 mg/l	Average	0.88 bar
Chem. Doses	None	Number of Elements	40	Average NDB	7.97 bar
Feed Solution Area	1692.84 m <sup>2</sup>	Average Feed Flow	6.25 m <sup>3</sup> /d	Flux	15.00 l/m <sup>2</sup> /h
Water Clean Index	RO Permeate SDFI < 1			Specific Energy	2.27 kWh/m <sup>3</sup>
System Recovery	91.27 %				

Stage	Element	SPW (l/d)	Feed Flow (m <sup>3</sup> /d)	Feed Press (bar)	Recirc Flow (m <sup>3</sup> /d)	Conc Flow (m <sup>3</sup> /d)	Conc Press (bar)	Perm Flow (m <sup>3</sup> /d)	Avg Flux (l/m <sup>2</sup> /h)	Perm Press (bar)	Reject Press (bar)	Perm TDS (mg/l)
1	BW30-100	4	74.16	8.68	0.00	398.76	8.48	112.11	17.16	0.00	0.00	5.06
2	BW30-400	6	300.78	8.14	0.00	114.91	7.53	187.86	14.89	0.00	0.00	13.67
3	BW30-100	1	113.91	8.93	0.00	13.21	8.32	71.71	11.79	0.00	0.00	11.81

Name	Feed	Adjusted Feed	Permeate (mg/L or l/cm <sup>3</sup> )								
			Concentrate			Permeate			Total		
			Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3			
NT4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
K	10.23	10.23	97.25	217.56	621.51	1.62	4.49	15.28	3.89		
Na	23.41	23.41	27.92	120.23	399.27	0.18	0.52	1.81	0.10		
Mg	0.43	0.43	1.15	3.97	7.73	0.00	0.00	0.00	0.00		
Ca	0.61	0.61	1.20	3.89	10.11	0.00	0.01	0.02	0.01		
Si	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
CO3	0.00	0.00	0.00	0.00	1.54	0.00	0.00	0.00	0.00		
HCO3	17.75	17.75	43.64	114.73	295.98	0.52	0.77	1.76	0.67		
NO3	28.43	28.43	87.61	163.19	403.37	0.34	6.30	31.67	5.37		
Cl	46.83	46.83	115.34	500.97	790.37	0.35	1.61	3.81	0.83		
F	0.81	0.81	0.06	1.07	3.18	0.00	0.01	0.03	0.01		
SO4	1.51	1.51	3.31	9.91	25.27	0.00	0.01	0.04	0.01		
SiO2	0.18	0.18	0.61	3.44	8.45	0.00	0.0	0.01	0.01		
Brom	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
CO2	6.11	6.11	6.16	6.51	7.10	6.18	6.27	6.55	6.26		
TDS	160.12	160.12	319.22	997.81	2573.65	5.66	13.07	11.91	11.24		
pH	6.67	6.67	7.64	7.40	7.73	7.71	7.94	7.69	7.3		

Permeate - this permeate by ROSA is calculated based on ACTIVE membrane area. **DISCLAIMER: NO WARRANTY, EXPRESSED OR IMPLIED, AND NO WARRANTY OF MERCHANTABILITY OR FITNESS, IS GIVEN.** Nalco Filtration Corporation and The Dow Chemical Company assume no liability for results obtained or damages incurred from the application of this information. Filtration Corporation and The Dow Chemical Company assume no liability, if as a result of customer's use of the ROSA membrane design software, the customer then is sued for alleged infringement of any patent now issued or controlled by the Filtration Corporation or the Dow Chemical Company.

**ROSA Detailed Report**

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Reverse Osmosis System Analysis for FULFILLMENT/Calculations  
 Project: Case 4 07-07-08 (1)

ROSA v6.1.4 Config:FB 0398786 .31  
 Case: 1  
 7/3/2008

**Design Warnings - Pass 1**

**CAUTION:** The concentrate flow rate is less than the recommended minimum flow. Please change your system design to increase concentrate flow rates.  
 (P=4.0 - PERCENT, Feed: 54.3 m<sup>3</sup>/d)

**Solubility Warnings - Pass 2**

-None-

**Stage Details -- Pass 2**

Stage 1	Element	Recovery	Perm Flow (m <sup>3</sup> /D)	Feed TDS (mg/L)	Feed Flow (m <sup>3</sup> /D)	Feed TDS (mg/L)	Feed Press (bar)
	1	0.09	16.81	3.83	188.05	160.12	9.60
	2	0.10	16.29	3.97	169.21	175.70	9.12
	3	0.10	16.03	4.16	152.84	194.18	8.10
	4	0.11	15.73	4.31	138.82	216.71	8.99
	5	0.13	15.48	4.43	121.00	243.98	8.33
	6	0.14	15.28	4.51	105.61	278.97	8.60
	7	0.17	15.18	4.57	90.32	325.18	8.57
Stage 2	Element	Recovery	Perm Flow (m <sup>3</sup> /D)	Feed TDS (mg/L)	Feed Flow (m <sup>3</sup> /D)	Feed TDS (mg/L)	Feed Press (bar)
	1	0.10	14.55	8.24	150.19	389.22	8.14
	2	0.10	13.97	9.28	118.04	474.43	7.95
	3	0.11	13.62	10.16	122.07	477.56	7.98
	4	0.12	13.28	10.18	108.45	536.25	7.63
	5	0.14	12.91	10.20	92.27	608.71	7.03
	6	0.15	12.48	17.20	82.33	703.07	7.40
	7	0.13	12.19	21.15	69.65	827.00	7.34
Stage 3	Element	Recovery	Perm Flow (m <sup>3</sup> /D)	Feed TDS (mg/L)	Feed Flow (m <sup>3</sup> /D)	Feed TDS (mg/L)	Feed Press (bar)
	1	0.10	11.36	25.70	114.91	997.91	6.08
	2	0.11	11.00	29.02	102.22	1101.27	6.20
	3	0.13	10.65	34.35	92.51	1252.55	6.58
	4	0.13	10.29	41.44	81.90	1388.07	6.59
	5	0.14	9.92	50.19	71.60	1581.62	6.53
	6	0.13	9.49	60.28	61.69	1827.74	6.44
	7	0.17	8.99	69.28	52.20	2178.27	6.29

Permeate Flux reported by ROSA is calculated based on ACTIVE membrane area. **DISCLAIMER: NO WARRANTY, EXPRESSED OR IMPLIED, AND NO WARRANTY OF MERCHANTABILITY OR FITNESS, IS GIVEN.** Fuller Filtrite Corporation and The Dow Chemical Company assume liability for results obtained or damages incurred from the application of this information. Fuller Filtrite Corporation and The Dow Chemical Company assume no liability, if as a result of customer's use of the ROSA membrane design software, the customer should be sued for alleged infringement of any patent not owned or controlled by Fuller Filtrite Corporation or The Dow Chemical Company.

**ROSA Detailed Report**

**Scaling Calculations**

	Raw Water	Pass 1 Adjusted Feed	Pass 1 Concentrate	Pass 2 Concentrate
pH	7.70	7.70	7.96	7.73
Langelier Saturation Index	0.35	0.36	0.91	0.55
Stiff & Davis Stability Index	0.00	0.00	0.83	-0.44
Tonnage Strength (Mole/l)	0.00	0.00	0.07	0.04
CaCO <sub>3</sub> (mg/l)	1402.98	1403.00	1187.11	2578.50
HCO <sub>3</sub> <sup>-</sup>	215.10	215.10	694.53	296.59
CO <sub>3</sub> <sup>2-</sup>	2.91	2.91	8.29	7.10
ClO <sub>3</sub> <sup>-</sup>	0.88	0.88	8.19	1.53
CaSO <sub>4</sub> (% Saturation)	0.67	0.63	4.01	0.05
BaSO <sub>4</sub> (% Saturation)	0.00	0.00	0.00	0.00
StrSO <sub>4</sub> (% Saturation)	0.00	0.00	0.00	0.00
CaF <sub>2</sub> (% Saturation)	26.45	26.45	927.63	37.33
SiO <sub>2</sub> (% Saturation)	6.76	6.76	21.20	6.14
Mg(OH) <sub>2</sub> (% Saturation)	0.00	0.00	0.02	0.00

Total Chlorine: 0.04 mg/l Cl added to feed

**ROSA Detailed Report**

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Reverse Osmosis System Analysis for FILMTEC™ Membranes  
 Project: Case # 09-07-08 (1)

ROSA v6.1.4 Config:FB 0308786 .31  
 Case: 3  
 7/10/2008

**Project Information:** Case 3 RO Recovery=60.0% RO Flux = 11.1 l/h/ft<sup>2</sup> Membrane RO Feed Flow as Case 1

**System Details**

Feed Flow to Stage 1	143761 Gpd	Feed Temperature	48.88 (°C)	Conductivity	
Raw Water Flow to System	143761 Gpd	Feed Conductivity	5076 µS	Feed Chlorine	
Feed Pressure	11.29 bar	Feed Temperature	12.0 (°C)	Concentrate	2.29 bar
Fouling Factor	0.85	Feed TDS	1401.00 mg/l	Average	1.62 hr
Chem. Dose	None	Number of Elements	16	Average NPD	5.67 bar
Feed Acidic Area	133776 MP	Average Trans. FT/ft <sup>2</sup>	15.55 l/h <sup>2</sup>	Trans. Rate	1.47 l/h <sup>2</sup>
Water Clean Index: Tertiary Effluent (Municipal) SDI = 3				Specific Energy	0.01 kWh/L

Stage	Element	#PV	#E	Feed Flow (GPD)	Feed Press (bar)	Reconc Flow (GPD)	Conc Flow (GPD)	Conc Press (bar)	Perm Flow (GPD)	Avg Flux (l/h/ft <sup>2</sup> )	Perm Press (bar)	Reconc Press (bar)	Perm TDS (mg/l)
1	BWFO 100	4	6	71876	11.24	0.00	401.87	10.08	518.89	15.83	1.50	0.00	18.75
2	BWFO 100	2	6	10117	8.73	0.00	256.10	8.32	109.76	13.99	0.00	0.00	24.26

Name	Feed	Adjusted Feed	Concentration (mg/L as Ion)		Permeate		
			Concentration		Stage 1	Stage 2	Total
			Stage 1	Stage 2			
NTS	0.00	0.30	0.00	0.00	0.03	0.00	0.00
K	252.48	252.49	460.07	124.76	4.50	0.22	5.84
Na	241.07	241.07	441.29	698.01	1.89	3.96	2.59
Mg	30.81	30.81	38.75	60.63	0.07	0.14	0.09
Ca	28.33	28.33	12.17	81.01	0.00	0.13	0.13
Si	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CO3	0.88	0.88	2.94	6.87	0.00	0.00	0.00
HCO3	213.10	213.10	396.86	613.33	2.01	4.01	3.62
NO3	26.78	26.78	100.69	121.70	1.32	3.69	3.66
Cl	166.67	166.67	801.70	1251.63	3.32	7.12	4.72
F	3.64	3.64	4.83	7.63	0.00	0.00	0.00
SO4	110.84	110.84	203.58	323.43	0.29	0.60	0.33
SR02	1.10	1.10	13.00	20.00	0.00	0.00	0.00
Throm	0.00	0.00	0.00	0.00	0.00	0.00	0.00
UO2	3.97	3.97	6.71	8.00	0.04	2.00	0.96
TDS	1402.08	1401.00	2562.08	4049.82	16.70	24.25	22.14
pH	7.70	7.70	7.87	7.95	5.83	6.00	5.89

Permeate flux reported by ROSA is calculated based on ACTIVE membrane area. **DISCLAIMER: NO WARRANTY, EXPRESS OR IMPLIED, AND NO WARRANTY OF MERCHANTABILITY OR FITNESS IS GIVEN.** Neither FilmTec Corporation or The Dow Chemical Company assume liability for results obtained or damages incurred from the application of this information. FilmTec Corporation and The Dow Chemical Company assume no liability, if as a result of customer's use of the ROSA membrane from software, the customer should be sued for alleged infringement of any patent not owned or controlled by the FilmTec Corporation nor The Dow Chemical Company.

**ROSA Detailed Report**

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Reverse Osmosis System Analysis for FULFILL™ Membranes  
 Project: Case # 09-07-08 (1)

ROSA v6.1.4 Config:FB 0398786 .11  
 Case: 1  
 7/10/2008

**Design Warnings**

None

**Solubility Warnings**

Temperature Solubility Index > 0  
 Salt & Dose Solubility Index > 0  
 CaF<sub>2</sub> (% Saturation) > 100%

Ammonia may be required. Consult your ammonia manufacturer for dosing and maximum allowable system recovery.

**Stage Details**

Stage 1 Element	Recovery	Perm Flow (m <sup>3</sup> /h)	1.5m <sup>3</sup> TD <sub>90</sub> (kg/d)	Feed Flow (m <sup>3</sup> /h)	Feed TDS (mg/l)	Feed Press (bar)
1	0.05	15.47	11.96	185.94	1403.00	11.54
2	0.09	14.90	13.05	170.47	1524.00	10.99
3	0.09	14.25	15.09	152.57	1674.27	10.71
4	0.10	13.85	17.78	141.20	1847.79	10.54
5	0.10	13.23	20.02	127.39	2090.81	10.30
6	0.11	12.84	24.70	114.01	2336.78	10.11

Stage 2 Element	Recovery	Perm Flow (m <sup>3</sup> /h)	1.5m <sup>3</sup> TD <sub>90</sub> (kg/d)	Feed Flow (m <sup>3</sup> /h)	Feed TDS (mg/l)	Feed Press (bar)
1	0.07	14.25	21.23	202.41	2562.09	9.72
2	0.07	13.45	27.77	188.10	2753.99	9.43
3	0.07	12.82	31.78	175.00	2961.91	9.16
4	0.07	12.18	36.46	161.82	3197.00	8.91
5	0.08	11.43	41.99	149.70	3457.80	8.60
6	0.08	10.73	48.22	138.21	3741.00	8.30

Notes: This report is generated by ROSA in calculation based on ACTIVE membranes. DISCLAIMER: NO WARRANTY, EXPRESSED OR IMPLIED AND NO WARRANTY OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. Neither Ch2M Hill or The Dow Chemical Company assume liability for results obtained or damages incurred from the application of the information. FilmTec Corporation and The Dow Chemical Company assume no liability, if as a result of customer's use of ROSA software from software, the customer should be sued for alleged infringement of any patent not owned or controlled by the FilmTec Corporation or The Dow Chemical Company.

ROSA Detailed Report

Scaling Calculations

	Raw water	Adjusted Feed	Concentrate
pH	7.70	7.70	7.95
Langelier Saturation Index	0.36	0.36	0.77
Stiff & Davis Stability Index	0.00	0.00	0.04
Ionic Strength (Mole/l)	0.02	0.02	0.07
TDS (mg/l)	1402.83	1103.00	4042.82
HCO <sub>3</sub>	215.10	215.10	613.55
Ca <sup>2+</sup>	2.91	2.91	8.07
Mg <sup>2+</sup>	0.83	0.83	6.87
CaSO <sub>4</sub> (% Saturation)	0.63	0.61	3.10
BaSO <sub>4</sub> (% Saturation)	0.00	0.00	0.00
StrSO <sub>4</sub> (% Saturation)	0.00	0.00	0.00
CaF <sub>2</sub> (% Saturation)	26.45	26.45	643.26
SiO <sub>2</sub> (% Saturation)	6.76	6.76	18.53
Mg(OH) <sub>2</sub> (% Saturation)	0.00	0.00	0.02

Total Hardness: 0.04 eq/l Cl added to feed

## Appendix C      NF Membranes: SR2 versus NF90

Table C-1 provides a brief comparison in terms of feed pressure for single element operation at various conditions. The SR2-2540 feed pressures are as per the experimental data provided by Victoria University whereas the NF90-2540's are the projected data by the ROSA software. The feed pressure range for NF90-2540 is based on the feed water temperature of 15 to 20 degree Celsius and fouling factor of 0.85. ROSA projections are attached.

The following table indicates that potential significant feed pressure reduction is expected for the proposed SR2 membranes and hence the same for power consumption.

**Table C-1: SR2-2540 Vs NF90-2540 – Element Feed Pressure Comparison**

Single Element Comparison	SR2-2540 Feed Pressure (Experimental Data)	NF90-2540 Feed Pressure (ROSA Projection Data)	(SR2 / NF90)%
<b><u>CASE 1:</u></b> 18LMH, 20% Element Recovery, 3.8L/min Flow	120	319 - 376	32 - 38%
<b><u>CASE 2:</u></b> 24LMH, 33% Element Recovery, 3.2L/min Flow	290	423 - 502	58 - 69%
<b><u>CASE 4:</u></b> 18LMH, 27% Element Recovery, 2.9L/min Flow	300	341 - 398	75 - 88%