**Cost Factors and Chemical Pretreatment Effects in the Membrane Filtration of Waters containing Natural Organic Matter**

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ABSTRACT

This paper compares the membrane processes available for water treatment. Membranes have the advantage of currently decreasing capital cost, a relatively small footprint compared to conventional treatment, generally a reduction in chemicals usage and comparably low maintenance requirements. Three membrane processes applicable to water treatment, micro- (MF), ultra- (UF), and nanofiltration (NF), are compared in terms of intrinsic rejection, variation of rejection due to membrane fouling and increase in rejection by ferric chloride pretreatment. Twelve different membranes are compared on the basis of their membrane pore size which was calculated from their molecular weight cut-off.

A pore size of <6 nm is required to achieve substantial (>50%) organics removal. For a fouled membrane this pore size is about 11 nm. UV rejection is higher than DOC rejection. Coagulation pretreatment allows a higher rejection of organics by MF and UF and the cut-off criterion due to initial membrane pore size is no longer valid.

A water quality parameter (WQP) is introduced which describes the product water quality achieved as a function of colloids, DOC and cation rejection. The relationship between log (pore size) and WQP is linear.

Estimation of membrane costs as a function of WQP suggests that open UF is superior to MF (similar cost at higher WQP) and NF is superior to tight UF. Chemical pretreatment could compensate for the difference between MF and UF. However, when considering chemicals and energy costs, it appears that a process operated at a higher energy is cheaper at a guaranteed product quality (less dependent on organic type). This argument is further supported by environmental issues of chemicals usage, as energy may be provided from renewable sources.

KEYWORDS

Coagulation, microfiltration (MF), nanofiltration (NF), natural organic matter (NOM), ultrafiltration (UF), water quality parameter (WQP).
The ferric chloride cost range was provided by Orica Watercare, Australia. The large range of costs was explained with variations in purity and delivery costs depending on the location of the facility. The effect of coagulant purity on membrane performance is unknown.

2.5 Analytical
Dissolved organic carbon (DOC) was analysed using a Skalar 12 (Skalar, The Netherlands) instrument. Ultraviolet/visible absorption was analysed with a Varian Cary 1E spectrophotometer. While samples were scanned from 190 to 500 nm, the results at 254 nm were used for calculations. Cation concentration was determined with a Perkin Elmer Optima 3000 spectrometer. Sample vials were cleaned with 1 M NaOH and 1 M H$_2$SO$_4$ solutions to remove organic and inorganic contamination, respectively.

RESULTS AND DISCUSSION

Membrane Characteristics

Twelve membranes were used in this study. The membranes were characterised by pure water flux and permeability, membrane resistance, molecular weight cut-off (as supplied by the manufacturers) and a calculated pore diameter (Table 2). The pore size calculations are based on an equation determined by Worch (1993) and the Stokes Einstein equation (see Schäfer (1999) for calculations and characterisation of surface roughness, contact angle and charge of the membranes used).

Rejection Characteristics of Clean Membranes

Rejection characteristics of all membranes were studied in detail and published elsewhere (Schäfer et al. (1999), Aoustin et al. (2000), Schäfer et al. (2000)). In this section the results obtained with the individual processes are summarised and illustrated as a function of calculated membrane pore size.

Figure 1 shows the rejection of DOC as a function of membrane pore size for various organic fractions. A clear cut-off can be seen where rejection drops from about 80% to 10%. This cut-off is around a pore size of 6 nm. The various organics are retained to a different extent depending on their size. The organics were characterised in detail elsewhere (Schäfer (1999)). Sizes were determined to be 1.6 to 2.7 nm as equivalent sphere diameters.

Comparing DOC to UV rejection, a higher rejection of UV absorbing compounds is observed (see Figure 2). This indicates a preferential removal of larger and more aromatic compounds over the entire range of membrane pore sizes.

Cation rejection is shown in Table 3. Only the NF membranes remove sodium. Calcium rejection increases gradually with decrease in pore size. Substantial removal is only achieved with the TFC membranes.

The rejection and membrane characterisation results indicate that for each application (and desired product quality) there will be an optimal membrane, which can be selected yielding highest flux and acceptable rejection for the contaminant of concern.

Rejection Characteristics of Fouled Membranes

Fouling changes the surface characteristics and pore size of membranes and these changes have an impact on the rejection behaviour. Figure 3 compares the organics rejection by fouled membranes with that of clean membranes as shown in Figure 1.

The cut-off where rejection of natural organics drops is shifted from about 6 to 11 nm due to fouling. The fouling layer consists of a deposit formed with calcium and IHSS HA as previously described (Schäfer et al. (1998)). Childress and Elimelech (1996) have reported a more negative membrane surface charge due to the deposition or adsorption of organics in the presence of calcium. This more negative surface charge may increase the rejection of the generally negatively charged natural organics.

Further, calcium causes the aggregation of organics and subsequent pore size reduction due to the deposition of aggregates. Both of these effects would also enhance organics rejection.

Rejection Characteristics with Coagulation (FeCl$_3$) Pretreatment

In MF and UF, where the pore sizes are larger than the cut-off required to remove a substantial amount of organics (6 nm), rejection can be increased by coagulant addition.

The coagulant, in this case ferric chloride (FeCl$_3$), precipitates and adsorbs natural organics on the precipitate surface. The particulates are subsequently retained which leads to an increased rejection of organics. The extent of increased removal is shown in Figure 4 for three types of organics and two ferric chloride dosages. The coagulant dosages are typical of those used in enhanced coagulation applications (Crozes (1995)).

The natural organics removal is higher for the higher coagulant dose and can reach levels similar to those of the small pore size membranes. However, the low rejection at low ferric chloride concentrations and the large scatter in data with organic type indicate that the removal is dependent on the water characteristics and thus potentially subject to considerable variation during water treatment.

Membrane Fouling Behaviour and Influence of Coagulation

In MF and UF, coagulation is used as a means of increasing natural organics rejection. The organics are adsorbed on a ferric oxyhydroxide precipitate which is retained by the membrane. This precipitated colloid can cause membrane fouling by pore blocking or cake deposition, a mechanism which depends on the membrane pore size and the conditions under which the precipitates are formed.

Flux ratios ($J/J_0$) is the ratio of flux to initial flux) over permeate volume are shown in Figure 5 and Figure 6 for MF and UF, respectively. Flux decreases with increasing ferric chloride dosage and the more open the membrane the larger is the effect. This is because the more open membrane with higher $J_0$ appears to be more sensitive to cake formation.

In NF, natural organics rejection is high and no coagulation pretreatment is required. However, since coagulation targets large, hydrophobic organics which foul NF membranes by precipitation and gel layer formation, coagulation pretreatment can control fouling.

This effect is shown in Figure 7, where $J/J_0$ is the ratio of permeate flux to flux at the beginning of the experiment. The flux declines rapidly and irreversibly without coagulation. If ferric chloride is added flux decline ceases.
This pretreatment effects the fouling and with the alteration of the deposit, also the rejection of the membrane. The foulant is bound to precipitates which are too large to foul the NF membranes. This pretreatment also modifies the rejection of solutes by a variation of the surface charge of the organic. Organic rejection decreases from 93% to 79% at pH 3 where a very positively charged precipitate is formed. The rejection of calcium generally increases from 55% to almost 99% at pH 3, while sodium rejection increases from 24 to 43% at these conditions (for details on these results see Schäfer (1999)).

Water Quality Parameter (WQP)

Fane (1996) proposed an overall water quality index for treatment based on pathogen, turbidity, colour and salt removal. This criterion was modified to suit the study in this project and is presented in Table 4.

Pathogens were not included in this study as 100% removal is assumed. However, for MF this may not be achieved under all operating conditions as reported by Jacangelo et al. (1995). Log removals of the virus MS2 bacteriophages (0.025 µm) reported as low as 0.4 (60%) for MF (0.2 µm), while a UF membrane (100 kDa) removed >6 log. Cryptosporidium parvum (4 to 6 µm in diameter) and Giardia muris (7 to 14 µm) cyst removal was complete (>6 log, below detection limit) by both MF and UF. The removal of viruses is thus a criterion which needs to be considered in the process choice. Log removal describes the number of orders of magnitude by which the feed concentration is removed and is defined as log (feed concentration / permeate concentration) (Ho and Sirkar (1992)).

As a summary criterion, the water quality parameter (WQP) is introduced. The maximum score for WQP is 300. The total score for each parameter suite (colloids, DOC, and ions) is 100. The columns are subdivided into equal fractions, resulting in total points of 25 for the individual colloid fraction, 33.3 for each organic fraction, and 50 for the major cations (Na+, Ca2+).

For colloids, stable primary colloids (in our other work described as “organic-particle-salt (OPS) systems”- colloids which are stabilised by organics) are assumed as these appear most abundant in natural waters. These colloidal systems are described in detail elsewhere (Schäfer et al. (1999)).

Ion rejection is represented by sodium and calcium rejection in the absence of organics. In the case of DOC rejection, solutions contain 0.5 mM CaCl2 (except for MF where calcium concentration is 2.5 mM).

The WQP values increase with membrane tightness as expected. The relationship between log (pore size) and WQP is linear (Figure 8). The CA-UF membrane performs overall as a UF membrane in the 5 kDa cut-off range.

If one further considers the cost of ferric chloride (see Table 8) and the energy cost (see Table 9) the advantage of a process which does not require chemical pretreatment becomes even more important. Recovery is defined as the product to feed volume ratio. It is limited by backwash and cleaning volumes for MF and UF, and by the maximum concentration in a module for NF and RO.

Energy costs are comparable or lower than the cost of ferric chloride (with the exception of RO due to osmotic effects due to high salt rejection). This does not include sludge treatment or the

Membrane and Energy Cost Estimation

The membrane materials selected for cost estimates are the MF PVDF (62.5 US$/m2), the UF CA (16.7 US$/m2), and the NF PA (20.8 US$/m2). Costs were provided by Leslie (1999) and originate from comparative studies at Water Factory 21 in Orange County (USA). Values are tabulated in Table 7. The selection was based on the comparability to membrane materials used in this study. The cost for MF is high, but PVDF is chosen as this appears to be the best membrane material despite other materials being installed currently. For polypropylene the cost will be about one third of the estimate and possibly lower for a submerged membrane system (Johnson (1999)).

Membrane life can be estimated in the order of five years, thus the membrane cost will be a maintenance cost as well as an investment cost.

Membrane cost was estimated from fluxes obtained in experiments and the membrane area required to produce 1000 m3/d product water. Figure 9 shows the membrane cost as a function of WQP (values were shown in Table 4) based on pure water fluxes.

Costs for the MF and open UF membranes are comparable. For tight UF membranes MWCO 1-5 kDa the costs increase to unacceptable levels and are in fact lower for the TFC-SR and –S membranes. The CA-UF membrane lies well in the UF range and is cost wise extremely competitive given the high WQP. It should be noted that for applications requiring turbidity removal only (WQP of 50 to 100) MF or loose UF have a major cost advantage.

When fluxes of fouled membranes are considered (Figure 10 and Table 5), the cost increases, but the overall trend is similar. Membrane costs for the TFC-S and –ULP membranes increase significantly compared to pure water due to the high salt rejection which causes a flux reduction due to an osmotic effect. The high salt rejections of these membranes are not usually required for surface water applications.

Cost values for membranes fouled with ferric chloride coagulant are shown in Table 6. With ferric chloride pretreatment the cost becomes prohibitive for MF operated at low flux and high ferric chloride dosage (see also no 3 in Figure 11). This is due to the larger membrane area required at low flux.

Ferric chloride increases the WQP for MF and UF and MF moves into the area of UF (see nos 1,2,3 and 4; the areas were defined previously based on rejection without pretreatment). At the low dosage cost is lowest at the highest initial fluxes. For the higher dosage (see no 4) the cost is not determined by initial flux, but fouling becomes the crucial criterion. At identical WQP, the 30 kDa UF membrane is lowest in cost, followed by low flux MF, then the 100 kDa and 10 kDa membranes.

The membrane cost for NF (TFC-SR) is comparable at a much higher WQP. Membrane costs are reduced with ferric chloride addition as fouling is reduced as was shown in Figure 7. However, the ferric chloride would add to the overall treatment costs.
consideration that energy can be provided from a renewable source which further supports the environmental argument for using NF when organic removal is important.

Finally, Table 10 shows a comparison of costs which originate from membranes, energy and chemicals addition. Costs are in US$ per 1000 m$^3$. Membrane costs are based on a membrane life of 5 years. The cost range for MF and open UF is the range of without pretreatment at the lower end and pretreatment with lowest cost ferric chloride at a dosage of 100 mg/L$^{-1}$ at the upper end. Costs will increase if higher quality coagulant is used or if the plant is at some distance to the ferric chloride supplier. The results show that chemical pretreatment costs affect treatment costs considerably and NF appears to be the choice for a stable water quality and cost.

**CONCLUSIONS**

This study demonstrates that membranes with tighter pore sizes are superior to more porous membranes in terms of rejection and membrane costs where such costs include capital and maintenance costs of the membrane installation, costs of chemicals used for pretreatment and energy costs.

This contradicts the conventional belief that a hybrid process consisting of chemical treatment and MF is cheaper than NF. While NF produces waters with a guaranteed and relatively stable quality, the effectiveness of chemical pretreatment depends strongly on the organic type and solution chemistry. Costs for chemical pretreatment are above the energy costs for NF if a substantial amount of organics is to be removed.

However, it is appreciated that for an application only requiring removal of turbidity (including microorganisms) MF or loose UF have a clear cost advantage.

A cost comparison of chemicals addition and energy consumption revealed that the additional energy required to operate NF is cheaper than the chemicals required to achieve a comparable organics removal with MF. While a more complete analysis is required including a complete assessment of environmental impact the results obtained should encourage some rethinking of current water treatment practices.

**ACKNOWLEDGEMENTS**

The Cooperative Research Centre for Water Quality & Treatment (Adelaide, Australia) is thanked for project funding. The assistance of Martina Fischer, Ursula Schwicker and Emmanuelle Aoustin with experimental work is appreciated. Material support from Fluid Systems (now Koch Membrane Systems, San Diego, USA) and Millipore (Australia) is also acknowledged.

**REFERENCES**


FIGURE CAPTIONS

Figure 1 Rejection of DOC as a function of calculated pore diameter (see Table 2 for membrane characterisation). Experimental conditions pH 7-8, 5-15 mg L⁻¹ as DOC organics, 0.5 mM CaCl₂, 1 mM NaHCO₃, stirred at 270 to 400 rpm, transmembrane pressures 1 bar (MF and UF 30-100 kDa), 3 bar (UF 1-10 kDa), and 5 bar (NF).

Figure 2 UV₂⁵⁴ rejection as a function of pore diameter. The DOC curve is adapted from Figure 1. Experimental conditions as in Figure 1.

Figure 3 Rejection at fouling conditions (12.5 mg L⁻¹ as DOC IHSS HA, 2.5 mM CaCl₂, pH 8) as a function of pore diameter. The line graphs are rejection results of unfouled membranes adapted from Figure 1 and Figure 2.

Figure 4 DOC rejection as a function of pore diameter with coagulation pretreatment compared to rejection with no pretreatment (shown as a line). Experimental conditions pH 7-8, 5-15 mg L⁻¹ as DOC organics, 0.5 mM CaCl₂, 1 mM NaHCO₃.

Figure 5 Ferric chloride addition in microfiltration (GVWP membrane, 2.5 mM CaCl₂, pH 7-8, 1 mM NaHCO₃, 20 mM NaCl, 5 mg L⁻¹ DOC IHSS HA).

Figure 6 Ferric chloride addition in ultrafiltration (100 kDa, 30 kDa and 10 kDa membranes, 0.5 mM CaCl₂, pH 7-8, 1 mM NaHCO₃, 20 mM NaCl, 5 mg L⁻¹ DOC IHSS FA).

Figure 7 Ferric chloride addition at fouling conditions in nanofiltration (TFC-SR membrane, 2.5 mM CaCl₂, pH 7-8, 1 mM NaHCO₃, 20 mM NaCl, 12.5 mg L⁻¹ DOC IHSS FA).

Figure 8 Water quality parameter as a function of clean membrane pore diameter. Values adapted from Table 4.

Figure 9 Membrane cost per 1000 m³/d capacity at clean water conditions over water quality parameter. Membranes are 1-GVWP high flux, 2-GVWP low flux, 3-100kDa UF, 4-30 kDa UF, 5-10 kDa UF, 6-5 kDa UF, 7-3 kDa UF, 8-1 kDa UF, 9-CA-UF, 10-TFC-SR, 11-TFC-S, 12-TFC-ULP.

Figure 10 Membrane cost per 1000 m³/d capacity at fouling conditions over water quality parameter. Membranes are 1-GVWP at high flux, 2-GVWP at low flux, 3-100kDa UF, 4-30 kDa UF, 5-10 kDa UF, 6-5 kDa UF, 7-3 kDa UF, 8-1 kDa UF, 9-CA-UF, 10-TFC-SR, 11-TFC-S, 12-TFC-ULP.

Figure 11 Membrane cost per 1000 m³/d capacity as a function of WQP. Membranes with no ferric chloride as shown in Figure 9. 1-GVWP high flux & low dose, 100kDa UF and 30kDa UF, 2- GVWP low flux & low dose and 10 kDa UF, 3-GVWP low flux, 4-30kDa UF, 5-GVWP low flux and high dose<100kDa UF<10kDa UF, 5-TFC-SR.

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7
Figure 8

\[ WQP = 232 - 83 \log d_P \]

Water Quality Parameter [-]

Pore Diameter [nm]

Figure 9

Figure 10

Figure 11

doi:10.1016/S0043-1354(00)00418-8
### TABLE 1
Solution composition as used in experiments.

<table>
<thead>
<tr>
<th>pH</th>
<th>NaHCO₃ [mM]</th>
<th>CaCl₂ [mM]</th>
<th>NaCl [mM]</th>
<th>Natural Organics¹</th>
<th>Inorganic Colloids²</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-8</td>
<td>1, 84</td>
<td>0.5, 56</td>
<td>20, 2, 935</td>
<td>5 – 12.5</td>
<td>10</td>
</tr>
</tbody>
</table>

Fouling Experiments

<table>
<thead>
<tr>
<th>pH</th>
<th>NaHCO₃ [mM]</th>
<th>CaCl₂ [mM]</th>
<th>NaCl [mM]</th>
<th>Natural Organics¹</th>
<th>Inorganic Colloids²</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-8</td>
<td>1, 84</td>
<td>2.5, 280</td>
<td>20, 2, 935</td>
<td>5 – 12.5</td>
<td>10</td>
</tr>
</tbody>
</table>

¹ Natural organics were humic acid, fulvic acid, natural organic matter or fractions of those.
² Inorganic colloids were monodispersed, spherical hematite colloids (diameters 40, 75, 250 and 500 nm).

### Table 2
Pure water membrane characteristics (flux, permeability, applied transmembrane pressure, membrane resistance, molecular weight cut-off (MWCO) and pore diameter) of the MF, UF and NF membranes used in experiments.

<table>
<thead>
<tr>
<th>Process Membrane</th>
<th>Flux [Lm⁻²h⁻¹]</th>
<th>Permeability [Lm⁻²h⁻¹ bar⁻¹]</th>
<th>Pressure [bar]</th>
<th>Resistance [m⁻¹]</th>
<th>MWCO [kDa]</th>
<th>Pore Diameter [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF GVWP</td>
<td>7968 ± 288</td>
<td>7968</td>
<td>1</td>
<td>4.51 · 10⁷</td>
<td>-</td>
<td>220</td>
</tr>
<tr>
<td>MF GVHP</td>
<td>7803 ± 308</td>
<td>7803</td>
<td>1</td>
<td>4.60 · 10⁷</td>
<td>-</td>
<td>220¹</td>
</tr>
<tr>
<td>UF PLHK</td>
<td>1320 ± 40</td>
<td>1320</td>
<td>1</td>
<td>0.03 · 10¹⁰</td>
<td>10³</td>
<td>18.2</td>
</tr>
<tr>
<td>UF PLTK</td>
<td>390 ± 20</td>
<td>390</td>
<td>1</td>
<td>0.09 · 10¹⁰</td>
<td>30³</td>
<td>9.62</td>
</tr>
<tr>
<td>UF PLGC</td>
<td>65 ± 5</td>
<td>21.7</td>
<td>3</td>
<td>1.66 · 10⁹</td>
<td>10³</td>
<td>5.18</td>
</tr>
<tr>
<td>UF PLCC</td>
<td>28 ± 3</td>
<td>9.3</td>
<td>3</td>
<td>3.85 · 10⁶</td>
<td>5¹</td>
<td>3.72</td>
</tr>
<tr>
<td>UF PLBC</td>
<td>22 ± 2</td>
<td>7.3</td>
<td>3</td>
<td>4.90 · 10⁶</td>
<td>3¹</td>
<td>2.84</td>
</tr>
<tr>
<td>UF PLAC</td>
<td>15 ± 2</td>
<td>5.0</td>
<td>3</td>
<td>7.18 · 10⁵</td>
<td>1¹</td>
<td>1.88</td>
</tr>
<tr>
<td>NF CA-UF</td>
<td>49.9 ± 4.2</td>
<td>10.0</td>
<td>5</td>
<td>3.6 · 10⁶</td>
<td>5¹</td>
<td>3.72</td>
</tr>
<tr>
<td>NF TFC-SR</td>
<td>45.8 ± 6.1</td>
<td>9.2</td>
<td>5</td>
<td>3.9 · 10⁶</td>
<td>&lt;0.18³</td>
<td>&lt;0.64</td>
</tr>
<tr>
<td>NF TFC-S</td>
<td>49.4 ± 5.9</td>
<td>9.9</td>
<td>5</td>
<td>3.6 · 10⁶</td>
<td>&lt;0.18³</td>
<td>&lt;0.64</td>
</tr>
<tr>
<td>NF TFC-ULP</td>
<td>19.4 ± 2.6</td>
<td>3.9</td>
<td>5</td>
<td>9.3 · 10⁶</td>
<td>&lt;0.18³</td>
<td>&lt;0.64</td>
</tr>
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</table>

¹ information supplied by Millipore.

### Table 3
Cation rejection as a function of membrane pore size in the absence of organics (0.5 mM CaCl₂, pH 7-8, 1 mM NaHCO₃, 20 mM NaCl).

<table>
<thead>
<tr>
<th>Pore Size [nm]</th>
<th>Sodium [%]</th>
<th>Calcium [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9 ± 0.3</td>
<td>1.4 ± 0.4</td>
<td>1.5 ± 0.1</td>
</tr>
<tr>
<td>1.9 ± 0.3</td>
<td>1.4 ± 0.4</td>
<td>1.5 ± 0.1</td>
</tr>
</tbody>
</table>

### Table 4
Water quality criteria for process evaluation and water quality parameter. The numbers are fractions of the rejection achieved. The sum of each parameter suite of 100 corresponds to a rejection of 100% of all fractions. Experimental conditions were pH 7-8, 5-15 mgL⁻¹ organic as DOC, 0.5 mM CaCl₂ (except for MF where calcium concentration is 2.5 mM). The values will depend on time (or permeate volume) and stirring regime. Membrane cost estimate based on pure water flux and a plant capacity of 1000 m³/d.

<table>
<thead>
<tr>
<th>Colloids</th>
<th>DOC</th>
<th>Ions</th>
<th>TOTAL</th>
<th>Membrane Cost Clean [US$]</th>
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</thead>
<tbody>
<tr>
<td>40 nm</td>
<td>75</td>
<td>250</td>
<td>500</td>
<td>49.9 ± 4.2</td>
</tr>
<tr>
<td>75 nm</td>
<td>250</td>
<td>500</td>
<td>10.0</td>
<td>100 kDa</td>
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<tr>
<td>250 nm</td>
<td>500</td>
<td>10.0</td>
<td>5.0</td>
<td>30 kDa</td>
</tr>
<tr>
<td>500 nm</td>
<td>10.0</td>
<td>5.0</td>
<td>25.2</td>
<td>10 kDa</td>
</tr>
<tr>
<td>1.9</td>
<td>3.7</td>
<td>18.2</td>
<td>220</td>
<td>MF GVWP</td>
</tr>
</tbody>
</table>

### Table 5
Water quality parameter for fouling conditions (2.5 mM CaCl₂, pH 7-8, IHSS HA). Plant capacity for cost estimate 1000 m³/d.

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>MF GVWP</td>
<td>46</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>56</td>
<td>325</td>
<td>1488</td>
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<tr>
<td>MF GVWP</td>
<td>46</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>56</td>
<td>325</td>
<td>1488</td>
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<tr>
<td>UF 100 kDa</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>2.5</td>
<td>2.8</td>
<td>3.0</td>
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<td>0</td>
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<tr>
<td>UF 30 kDa</td>
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<td>25</td>
<td>25</td>
<td>3.7</td>
<td>4.0</td>
<td>3.3</td>
<td>0</td>
<td>0</td>
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<td>1740</td>
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<td>UF 10 kDa</td>
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<td>25</td>
<td>25</td>
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<td>18.7</td>
<td>17.0</td>
<td>0</td>
<td>1.3</td>
<td>159</td>
<td>20466</td>
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<tr>
<td>UF 5 kDa</td>
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<td>25</td>
<td>25</td>
<td>29.3</td>
<td>27.3</td>
<td>24.7</td>
<td>0</td>
<td>1.0</td>
<td>182</td>
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<td>UF 3 kDa</td>
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<td>25</td>
<td>25</td>
<td>28.7</td>
<td>28.0</td>
<td>25.7</td>
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<td>6.8</td>
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<tr>
<td>UF 1 kDa</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>30.0</td>
<td>29.0</td>
<td>28.7</td>
<td>0</td>
<td>6.6</td>
<td>194</td>
<td>46389</td>
</tr>
<tr>
<td>NF CA-UF</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25.3</td>
<td>23.6</td>
<td>19.1</td>
<td>6.3</td>
<td>7.2</td>
<td>182</td>
<td>17333</td>
</tr>
<tr>
<td>NF TFC-SR</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>24.7</td>
<td>31.3</td>
<td>23.0</td>
<td>18.7</td>
<td>33.8</td>
<td>232</td>
<td>29782</td>
</tr>
<tr>
<td>NF TFC-S</td>
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<td>25</td>
<td>25</td>
<td>30.0</td>
<td>27.9</td>
<td>31.8</td>
<td>41.0</td>
<td>47.2</td>
<td>278</td>
<td>17687</td>
</tr>
<tr>
<td>NF TFC-ULP</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25.2</td>
<td>26.8</td>
<td>31.8</td>
<td>42.5</td>
<td>45.2</td>
<td>272</td>
<td>45614</td>
</tr>
</tbody>
</table>

² values adapted from Table 4 as fouling with calcium and organics only considered here.

* flux values corrected for low flux by a factor 10 from experimental value (1750 to 175 Lm⁻²h⁻¹) due to lower permeate pressure drop of flat sheet membranes.
### Table 6 Water quality parameter for pretreatment with ferric chloride (2.5 mM CaCl₂, pH 7-8, IHSS HA). Plant capacity for cost estimate 1000 m³/d.

<table>
<thead>
<tr>
<th>Rejection [%]</th>
<th>Quality and Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>FeCl₃ 25 mgL⁻¹/100 mgL⁻¹</td>
</tr>
<tr>
<td>MF GVWP 100</td>
<td>10-39 / 48.83</td>
</tr>
<tr>
<td>MF GVWP #100</td>
<td>10-39 / 48.83</td>
</tr>
<tr>
<td>UF 100kDa 100</td>
<td>35-90 / 77</td>
</tr>
<tr>
<td>UF 10 kDa 100</td>
<td>67-84 / 86</td>
</tr>
<tr>
<td>NF TFC-SR 100</td>
<td>94 / 79</td>
</tr>
</tbody>
</table>

* range depending on organic type.

### Table 7 Membrane cost based on Water Factory 21 Experience (Leslie (1999)).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MF Polypropylene</td>
<td>31</td>
<td>650</td>
<td>2.19</td>
</tr>
<tr>
<td>MF PVDF</td>
<td>40</td>
<td>2500</td>
<td>62.5</td>
</tr>
<tr>
<td>UF CA</td>
<td>90</td>
<td>1500</td>
<td>16.7</td>
</tr>
<tr>
<td>NF Polyamide</td>
<td>48</td>
<td>750 - 1000</td>
<td>15.6 – 20.8</td>
</tr>
<tr>
<td>RO Polyamide</td>
<td>50</td>
<td>&lt; 500</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>RO CA</td>
<td>50</td>
<td>500</td>
<td>&lt; 10</td>
</tr>
</tbody>
</table>

### Table 8 Ferric chloride cost as a function of dosage for a 1000 m³/day plant capacity. Range of costs of ferric chloride used was 0.29 to 7.1 US$/kg depending on largely location of water treatment plant and coagulant quality.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>25</td>
<td>7.3-177.5</td>
<td>29.4-710.0</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>0.007-0.18</td>
<td>0.029-0.71</td>
</tr>
</tbody>
</table>

### Table 9 Typical recoveries, transmembrane pressures, power requirements, and resulting energy costs based on applied pressures with an overall motor/pump efficiency of 40%. Assumed energy cost 0.05 US$/kWh.

<table>
<thead>
<tr>
<th>Recovery</th>
<th>Pressure [kPa]</th>
<th>Consumption [%]</th>
<th>Energy cost [US$/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF 90 - 98</td>
<td>100</td>
<td>77.5 - 70.8</td>
<td>0.004 - 0.0035</td>
</tr>
<tr>
<td>UF 90 - 98</td>
<td>100</td>
<td>77.5 - 70.8</td>
<td>0.004 - 0.0035</td>
</tr>
<tr>
<td>UF 90 - 98</td>
<td>300</td>
<td>231.5 - 212.5</td>
<td>0.012 - 0.011</td>
</tr>
<tr>
<td>NF 75 - 95</td>
<td>500</td>
<td>463.3 - 365.5</td>
<td>0.023 - 0.018</td>
</tr>
<tr>
<td>RO 50 - 80</td>
<td>1000</td>
<td>1389 - 868.3</td>
<td>0.070 - 0.043</td>
</tr>
</tbody>
</table>

### Table 10 Comparison of WQP as well as membrane, energy and chemical costs for selected membranes. It has been assumed that membranes last for 5 years.

<table>
<thead>
<tr>
<th>COSTS [US$/1000m³]</th>
<th>WQP [-]</th>
<th>Clean Membrane</th>
<th>Fouled Membrane</th>
<th>FeCl₃ Fouled Membrane</th>
<th>Energy Cost</th>
<th>FeCl₃ Cost 25 mgL⁻¹</th>
<th>FeCl₃ Cost 100 mgL⁻¹</th>
<th>Total*</th>
</tr>
</thead>
<tbody>
<tr>
<td>MF GVWP</td>
<td>58 - 183</td>
<td>0.18</td>
<td>0.82</td>
<td>4.88</td>
<td>1.5 – 1.4</td>
<td>7.34 – 177.5</td>
<td>29.4 – 710</td>
<td>2.2 – 35.8</td>
</tr>
<tr>
<td>MF GVWP #100</td>
<td>58 - 183</td>
<td>1.78</td>
<td>8.15</td>
<td>47.7</td>
<td>0.15 – 0.14</td>
<td>7.34 – 177.5</td>
<td>29.4 – 710</td>
<td>8.3 – 77.3</td>
</tr>
<tr>
<td>UF 100 kDa</td>
<td>108 - 177</td>
<td>0.65</td>
<td>4.77</td>
<td>6.66</td>
<td>1.5 – 1.4</td>
<td>7.34 – 177.5</td>
<td>29.4 – 710</td>
<td>6.2 – 37.4</td>
</tr>
<tr>
<td>UF 30 kDa</td>
<td>112 - 194</td>
<td>1.50</td>
<td>3.40</td>
<td>3.40</td>
<td>1.5 – 1.4</td>
<td>7.34 – 177.5</td>
<td>29.4 – 710</td>
<td>4.8 – 34.3</td>
</tr>
<tr>
<td>UF 10 kDa</td>
<td>159 - 191</td>
<td>11.2</td>
<td>11.9</td>
<td>7.78</td>
<td>4.6 – 4.2</td>
<td>7.34 – 177.5</td>
<td>29.4 – 710</td>
<td>16.1 – 41.8</td>
</tr>
<tr>
<td>UF 5 kDa</td>
<td>182</td>
<td>13.6</td>
<td>14.1</td>
<td>14.1</td>
<td>4.6 – 4.2</td>
<td>-</td>
<td>-</td>
<td>18.5</td>
</tr>
<tr>
<td>UF kDa</td>
<td>189</td>
<td>17.3</td>
<td>18.2</td>
<td>18.2</td>
<td>4.6 – 4.2</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>UF 1 kDa</td>
<td>194</td>
<td>25.4</td>
<td>27.2</td>
<td>27.2</td>
<td>4.6 – 4.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>UF 10 kDa</td>
<td>182</td>
<td>9.5</td>
<td>11.3</td>
<td>11.3</td>
<td>9.3 – 9.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NF CA-UF</td>
<td>232</td>
<td>10.3</td>
<td>14.0</td>
<td>14.0</td>
<td>9.3 – 9.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NF TFC-SR</td>
<td>278</td>
<td>9.7</td>
<td>25.0</td>
<td>25.0</td>
<td>9.3 – 9.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>NF TFC-ULP</td>
<td>272</td>
<td>25.0</td>
<td>39.6</td>
<td>39.6</td>
<td>9.3 – 9.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Flux and pressure reduced by a factor of 10.

* Cost calculated for lowest ferric chloride quality and cost. Range is cost without pretreatment to pretreatment with lowest cost ferric chloride at a dosage of 100 mgL⁻¹.