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Performance of a vibratory shear membrane filtration system during the treatment of magnetic ion exchange process concentrate

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HIGHLIGHTS

- Vibratory shear enhanced processing evaluation for the first time on magnetic ion exchange process concentrate.
- Fouling prior to cleaning-in-place every 14 batches leads to lengthened batch times.
- With 75%, 80% and 85% batch recoveries, more than 98% removal of DOC in MIEX waste was achieved.

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ABSTRACT

The performance of a vibratory shear enhanced processing (VSEP) unit used to treat waste generated from a magnetic ion exchange (MIEX) process is assessed. The unit was fitted with a NF-270 membrane (97% nominal rejection of $MgSO_4$) with an internal membrane surface area of 37 m^2. The vibration amplitude of the module was set at 12.7 mm. The system removes greater than 97% dissolved organic carbon as well as 70 − 85% multivalent solutes (Mg^{2+}, Ca^{2+}, SO_4^{2-}) from the MIEX waste. The permeate generated was high in salt and was successfully recycled to reduce the brine requirement for MIEX resin bead regeneration. Early operation in recirculating batch mode examined the effect of volumetric recoveries (in the permeate) ranging from 75–85%. Higher recovery had no significant influence on the performance of the system. System chemical cleaning was carried out every 14–16 batches. Batch durations generally extended in each subsequent cycle prior to cleaning, with the last batches taking up to five times longer than the first batch. The installation of VSEP has resulted in a reduced frequency of waste disposal from the facility and has also reduced the amount of make-up brine required for resin regeneration by 78%.

1. Introduction

In practice, inland groundwater treatment is significantly more complex than seawater desalination [1]. Seawater desalination operations utilise reverse osmosis to remove salts from sea water. Concentrate formed by desalination processes can be directly discharged into the ocean as there is little effect on the overall salinity of the ocean [2]. On the other hand, inland water treatment does not offer a straightforward method of concentrate disposal.

Concentrates generated as waste from inland water treatment plants are complex, and depending on the technology used, the final composition of the concentrate can vary significantly [3]. The concentrate may contain organic compounds, inorganic salts, microbacterium and viruses [4]. Incorrect discharge of concentrate has the potential to damage the environment, reduce public acceptance and present financial risks through penalties [5]. Concentrate discharge to surface waters can affect the temperature, salinity and concentration of the receiving water.

Inefficient purification processes can result in the deterioration of water quality in a number of aspects. Although there are few published reports linking organic pollutants and health effects, the presence of low molecular weight hydrocarbons does give rise to problems in drinking water [6]. Microbial contamination of drinking waters via waterborne pathogens has the potential to cause severe diarrhoeal diseases [7].

Dissolved organic matter is difficult to remove via conventional water treatment technologies [8]. Although membrane filters can effectively remove effluent organics from waste water streams, membrane fouling remains a significant drawback [9]. To ameliorate membrane fouling, additional processes such as flocculation, adsorption and ion exchange have been explored to remove organic matter from bulk water

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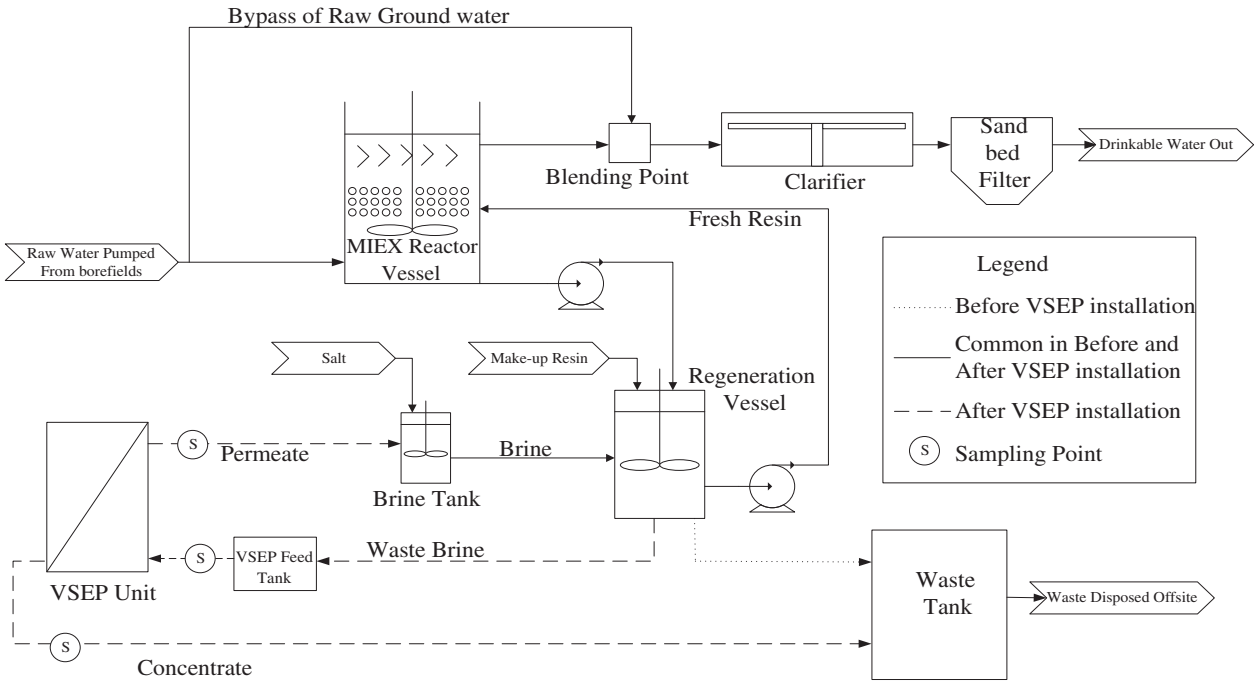

Fig. 1. The general layout of Wanneroo GWTP. Raw water is treated by the MIEX reactor vessel and sent to the clarifier and bed filters. Resin beads are regenerated in the regeneration vessel. Brine is a critical component in the regeneration process. The installation of VSEP at Wanneroo GWTP allows for MIEX waste concentrate to be treated and partially reused as make-up brine for the regeneration vessel. The MIEX waste prior to VSEP installation is sent to the waste tank (seen in the dotted line). Post-VSEP installation (dashed line) shows that VSEP concentrate is sent to the waste tank and the permeate is sent to the brine tank.

streams [10]. An example of an ion exchange system is the magnetic ion exchange process (MIEX) currently installed to treat groundwater at Wanneroo in Western Australia.

Magnetic ion exchange (MIEX) is a water treatment technology that uses magnetic beads to remove contaminants such as dissolved organic compounds from groundwater [11]. MIEX resins are approximately 180 μm in diameter. They provide high surface area for the rapid exchange of dissolved organic carbon (DOC) and chloride ions on the active sites of the resin. MIEX resins have been shown to remove more than 80% of DOC and 85% of UV absorbance from bulk raw waters [12]. Organic matter removed by the MIEX resins ranged from 500–1000 Da in molecular weight. Spent (i.e. fully loaded with organics) beads can be regenerated by mixing with highly concentrated salt solutions. Within this regeneration phase, MIEX waste is formed that is particularly highly concentrated in salt and organics.

At Wanneroo Groundwater Treatment Plant in Western Australia, Australia, the current method used to treat waste is blending. Blending is not a conventional way to treat concentrate. The technique involves mixing a concentrate stream such as MIEX waste with a less concentrated waste stream such as downstream filtrate to achieve a stream that is at a permissible concentration for direct discharge [13,14]. After blending, treated concentrate is collected in a waste tank for storage. Stored waste is later removed by a specialist company at significant cost.

To reduce the expense associated with concentrate disposal, the ideal approach is to eliminate or reduce the amount of waste produced. One option to do this is to employ volume reducing technology known as vibratory shear-enhanced processing (VSEP), which uses dynamic filtration to improve flux and control fouling phenomena [15]. The vigorous vibrational motion generates shear waves that act along the membrane surface to lift solids and foulants away from the surface and into the bulk flow. In the past, VSEP has been utilised in the paper milling, yeast treatment, dairy and water treatment industries [16].

A recent study by Nurra et al. utilised VSEP in order to dewater microalgae for use in biodiesel production [17]. Membrane filtration demonstrated more suitability as they did not disrupt fragile cells, unlike the centrifugation. The study compared the use of VSEP to conventional cross-flow filtration technology. Results showed that the dynamic forms of filtration were able to achieve high permeabilities and permeate flow rates, in some cases doubling that of conventional filtration that was attributed to the elimination of fouling. The filter pack consists of stacked circular membranes separated by gaskets and permeate collectors. The vertical shaft is spun in azimuthal oscillations that vibrate the base of the filter pack. The generated shear varies sinusoidally with time and it is the use of this resonance which minimizes the power requirements for vibration formation.

Vaneeckhaute applied VSEP technology to remove macronutrients from digestate, a product produced from co-digestion of animal manure [18]. The primary functionality of the VSEP was to remove macronutrients ranging from nitrogen, phosphorus, potassium, sodium, calcium and magnesium. Filtration via VSEP was able to remove 93% of nitrogen and 59% of phosphorus.

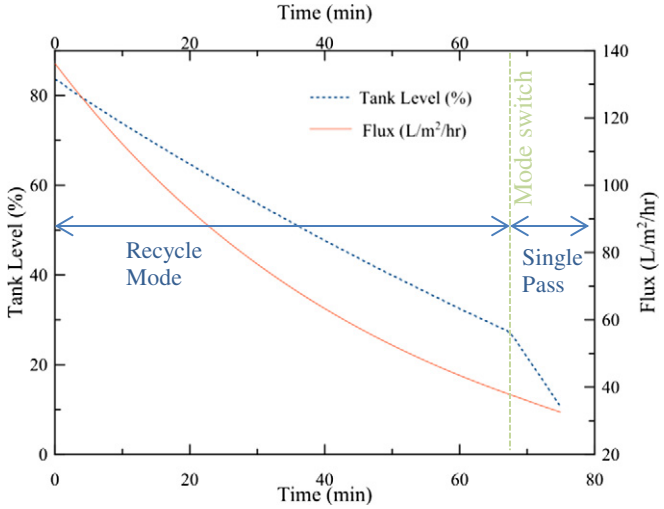

Fig. 2. The flux change over the course of a VSEP batch.

Table 1
Concentrations of the major components of the MIEX waste stream including monovalent and divalent solutes.

MIEX waste	Value
Calcium (mg/L)	260
Chloride (mg/L)	50,200
Magnesium (mg/L)	46.7
Silicon (mg/L)	5.4
Sodium (mg/L)	34,600
Sulphate (mg/L)	5080
TDS summation (mg/L)	91,000
DOC (mg/L)	5418
Colour (TCU)	>10,000
pH	7.3
Turbidity (NTU)	9.2

The use of VSEP to treat municipal waste water was explored by Zouboulis and Petala [19]. Using four different membrane types (MF, UF 10 kDa, UF 100 kDa and NF), they determined that high shear rates caused by vibration ensured that the permeate flux remained stable after a period of time and the hydrodynamic behaviour was satisfactory enough to meet the standards required to reduce the organic load in the leachate. Their results indicated that the combination of microfiltration or ultrafiltration with nanofiltration was optimal for treating municipal waste.

VSEP was installed at Wanneroo to treat waste generated via the MIEX process. Concentrate is fed into the VSEP unit via a storage tank. Prior to the installation of VSEP, waste concentrate generated onsite was sent into a tank collecting all wastes generated throughout the plant. The waste tank consists of a mixture ranging from concentrate to highly viscous filter cake from filter bed processes. By treating the waste generated from the MIEX procedure, a significant reduction in the amount of waste to be discharged was observed. Fig. 1 shows the path of concentrate to disposal prior to and after the installation of VSEP at Wanneroo GWTP.

The MIEX waste treated via VSEP exits in the form of permeate and concentrate. Although a majority of the concentrate is recycled back into the VSEP unit, leftover concentrate is sent to the waste tank. Permeate formed via VSEP is the desired product of the installation, as it's characteristics include high salt content and low dissolved organic carbon levels. This makes the permeate ideal for use as make-up brine, a key material required for MIEX resin regeneration. This paper examined the performance of the VSEP unit in detail. MIEX concentrate was feed into the system, and major components of the upstream and downstream of the VSEP unit were explored with respect to both organics and dissolved solutes. Time resolved flow and composition measurements throughout batch operations are investigated to elucidate the flux through the membrane and the varying membrane performance. Lastly, the major benefits resulting from reducing volume of waste disposed and the salt required for make-up brine were discussed.

Table 2
Concentration of major solutes in the feed stream over course of batch.

	Sample: recirculation mode			Sample: single pass mode	
Component	80% level	63% level	46% level	27.5% level	5% level
Ca^{2+} (mg/L)	260	331	407	614	629
Cl^{-} (mg/L)	50,200	49,100	49,700	47,100	47,200
Mg^{2+} (mg/L)	46.7	54.9	65.4	90.0	90.9
Si (mg/L)	5.4	5.8	6.8	9.5	12.0
Na^{+} (mg/L)	34,600	35,100	36,400	38,600	38,900
SO_4^{2-} (mg/L)	5080	3870	6510	9230	9320
TDS (mg/L)	91,000	87,000	94,000	97,000	99,000

Table 3
Typical permeate ions composition at start (t = 5) and completion of a batch.

Characteristic	Permeate (t = 5 min)	Permeate (t = final)
Na (mg/L)	30,500	33,500
Ca (mg/L)	93.5	94.3
Cl (mg/L)	48,600	50,800
TDS (mg/L)	81,000	87,000
pH	9.2	9.2

2. Materials & methods

2.1. MIEX concentrate

The MIEX concentrate was obtained from Wanneroo groundwater treatment plant. The plant is located approximately 25 km north of Perth in Western Australia (−31.722871, 115.852915) supplying 25,757 ML in 2014, roughly 10% of the total potable water supplied to the great Perth area [20]. A 2 L sample of waste product from the MIEX process was collected for characterisation. Thereafter, VSEP feed, permeate, concentrate and from the VSEP process was collected in <1.2 L samples on a weekly basis.

2.2. VSEP module

The VSEP filter P-mode is a pilot scale module manufactured by New Logic International (USA). The filter pack consists of an annular shaped membrane with outer and inner radii. The shaft used to drive the vibrational movement from the motor source is 1.864 m in height. A detailed description of the VSEP technology can be found in a paper by Culkin and Monroe [21], with further details available from New Logic International [22].

2.3. Tested membrane

A DowTech nanofiltration (NF-270) membrane was fitted into the VSEP filter pack. The used membrane was flat-disk modules with an effective area of 37 m^2. Specification tests exploring the membrane under test conditions of 2000 mg/L $MgSO_4$, 0.48 MPa, 25 °C and 15% recovery observed a stabilised salt rejection of 97%. Additionally the maximal operating temperature is 45 °C and the operating pH range is 3–10 [23].

2.4. Process operation

During filtration, the system operates at a constant feed pressure of 2400 kPa and a constant concentrate flow of 3.4 m^3/h. In a typical batch cycle, the empty tank was filled to 82.5% volume with the MIEX waste. Filtration begins upon reaching this threshold. Filtration occurs with the concentrate stream recycled to the feed tank until the level falls to 22.5–27.5%. The precise final tank level is governed by the desired batch recovery percentage. When the tank level dropped below 22.5%–27.5%, the system switched into single pass mode via an automated valve. The concentrate stream flowed directly to the waste tank. This mode of operation continued until the tank level reached its minimal threshold of 5% and the filtration ceased. The remaining

Table 4
Solute rejection percentages for calcium, chloride, magnesium, silicon, sodium and sulphate.

Tank level (%)	80	63	46	25	5
Calcium (%)	64.0	70.9	76.5	84.8	85.2
Chloride (%)	21.3	17.3	16.7	9.6	11.2
Magnesium (%)	47.1	52.6	60.7	71.6	71.6
Silicon (%)	42.6	43.1	50.0	63.2	70.0
Sodium (%)	11.8	7.4	9.9	13.2	13.9
Sulphate (%)	87.3	77.5	81.6	79.6	77.6

Table 5
Organic properties of feed and permeate samples taken at the beginning and end of batch.

	Feed (start of batch, 5 min after start)	Feed end of batch	Permeate (start of batch)	Permeate (end of batch)
Dissolved organic carbon (mg/L)	8392	15,290	228	370
Ultraviolet absorbance (UV_{254}) (cm^{-1})	359	664	7.7	12.1
Specific ultraviolet absorbance ($SUVA_{254}$) (L/mg·M)	4.28	4.34	3.39	3.26
Conductivity (S/m)	9860	10,430	5470	10,350
pH	12.08	11.80	11.95	11.86
Weight average molecular weight (M_w) (Da)	1552	1522	1007	1030

contents were drained into the same waste tank and the vessel underwent flushing prior to the next batch.

Fig. 2 shows the typical behaviour of the VSEP unit in terms of flux and tank level over the course of a single batch. The tank level falls steadily over the course of the batch until the shift to single pass mode (in this particular run at 27.5% tank level), at which point the tank level falls at an increased rate as concentrate is no longer recycled to the tank. The flux is highest at the start of the batch but reduces significantly throughout the course of the cycle. The increased concentration of organics in the feed through recycling is largely responsible for the reduction in permeate flux. It is likely that gradual build-up of non-permeating components at the membrane surface over the batch causes a concentration gradient to form, thus creating a phenomenon called concentration polarization that lowers concentration difference of any permeating components between the feed and permeate side of the membrane. Furthermore, the increasing salt content at the feed side results in an increase in osmotic pressure. As the system operates at constant feed pressure, the osmotic pressure offsets the driving pressure resulting in a decrease in flux. A similar observation was made by Shi et al. who attributed the reduction in flux to the combined effects of fouling and build-up of osmotic pressure in the VSEP feed solution [24].

2.5. Bulk/inorganic and organic analyses of the samples

Samples of MIEX waste and VSEP feed and permeate (at different % tank levels during a batch) were collected and analysed for different bulk, inorganic and organic parameters. Bulk and inorganic analyses were outsourced to ChemCenter in Western Australia [25]. Onsite measurements of pH and conductivity were taken directly after sampling. Samples were 0.45 μM filtered for all organic analyses and were carried out in the laboratories of Curtin University. Dissolved organic carbon (DOC) measurement of the MIEX waste and VSEP feed samples were carried out using the UV/persulfate oxidation method according to the standard method 5310C with a Shimadzu TOC-Vws Total Organic Carbon analyser [26]. Due to interference caused by the high salt concentration in the VSEP permeate, the DOC concentrations of these samples were determined using the high temperature combustion method with a Shimadzu TOC-$L_{CSH/CSN}$ Total Organic Carbon analyser, according to the standard method 5310B [26]. The UV absorbance at 254 nm (UV_{254}) of all samples was measured using a Cary 60 UV–Vis Spectrophotometer (Agilent Technologies, California, USA) with a 1 cm quartz cell. Specific UV_{254} absorbance ($SUVA_{254}$), an indicator of aromatic content and other conjugate functional groups of organic matter, was calculated based on the equation [(UV_{254} / DOC) * 100] [27]. To determine the molecular weight distribution of the organics in the samples, an analytical scale high performance size exclusion chromatography (HPSEC) was employed and calibrated using polystyrene sulfonate (PSS) standards (M_w 208 to 81800 Da) [28] and weight-average molecular weights (M_w) of the samples were calculated according to the method by Zhou et. al. [29].

2.6. VSEP cleaning methods

Between batches, a manual flush of the system occurs. During this time, dechlorinated water is used to flush the filter pack and lines for the duration of 400 s. Cleaning in Place (CIP) occurs every 14 batches. Each CIP begins with the water flush followed by a dosage of an acidic (Hydrex 4703) cleaner. The system then follows with a dechlorinated water flush for 750 s. Lastly alkaline (Hydrex 4705) is dosed into the CIP tank and recirculation of the cleaning solution occurs. The system continues to flush until the contents of the CIP tank are removed. Post-chemical cleaning, another water flush is performed prior to commencing the next batch. Although CIP was programmed to operate every 14 batches, a number of batches were interrupted and those particular batches were not incorporated into the results.

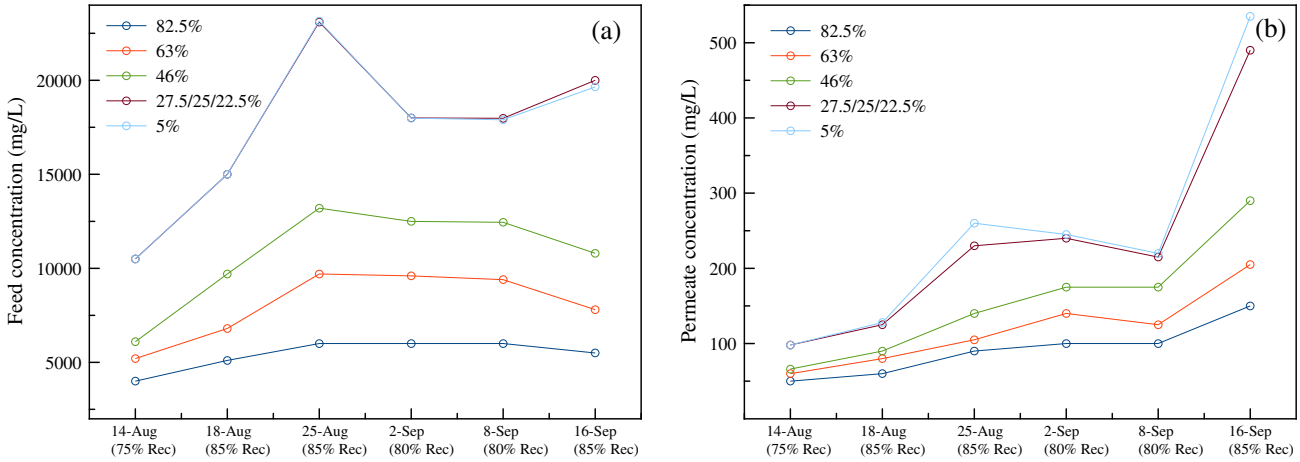

Fig. 3. (a & b). Feed and permeate concentration change per batch at different permeate recoveries.

3. Results & discussion

3.1. VSEP feed analysis

3.1.1. Characterisation of the VSEP feed (MIEX waste)

The MIEX waste sample characteristic is summarised in Table 1. The very high organic concentration and turbidity indicate that the MIEX stream is highly concentrated compared to stream previously processed by VSEP systems, which have ranged from 2000 mg/L in brackish water [30] to 4100 mg/L in the case of landfill leachates [19].

3.1.2. Change in solute concentration in the feed stream

Table 2 shows the change in the major solutes within the feed tank over the course of the batch. Importantly the concentrations of solutes are not expected to change significantly between the 27.5% and 5% sample points as no additional recycling of concentrate occurs during this phase and this was observed to be the case. The most significant changes in feed concentration can be seen for calcium, magnesium and silica, which are all multivalent solutes. These solutes doubled in their original concentration over the course of the batch. As expected for the NF-270 membrane, monovalent ions such as chloride and sodium were not significantly concentrated in the tank during recycle mode. The chloride level in the batch tank decreases slightly over the course of the process, which is unexpected and may be within the bounds of the error in the analysis and/or sampling process.

3.2. Permeate & feed analysis

3.2.1. Characteristic change in permeate over the course of a batch

Feed and permeate samples were taken at distinct intervals within the batch (80% tank level, 63% tank level, 46% tank level, 27.5% tank level and 5% tank level). The permeate concentrations at the beginning and end of a batch cycle are indicated in Table 3. In all cases, solute concentration of the permeate increases over the course of the process. This was expected given that the concentration of the VSEP feed increases throughout the course of the batch.

3.2.2. Solute rejection of the NF-270 membrane

By comparing the difference in dissolved solid concentrations of the VSEP feed stream to that leaving in the permeate, the rejection percentage of major solutes was estimated. Table 4 shows the rejection percentage for major solutes at the sampled points in a 80% permeate recovery VSEP batch. The majority of multivalent ions: magnesium, calcium and sulphate ions are rejected by the membrane (>70%). This is lower than unexpected as the specified rejection of $MgSO_4$ is greater than that of 97% [23]. Interestingly, the rejection of monovalent ions such as sodium and chloride was significantly lower at around 11–14%. This is lower than the expected values of rejection based on the Dowtech specification sheet for NF-270. However the specification of the membrane by Dowtech used a less concentrated feed and operated at lower recoveries (15%). Consistent with the purpose of the VSEP treatment of MIEX waste, multivalent solutes are rejected and monovalent solutes such as sodium are retained. Observations were different to those seen previously where the findings of Zouboulis & Petala who used VSEP to treat landfill leachates, as the rejection percentage rejection decreased as feed became more concentrated and flux across the membrane decreased [19]. Over the course of the batch, positively charged solute rejection increased and negative charge solute rejection decreased over the batch. It is possible at the operating pH, the membrane could be negatively charged. The electroneutrality could encourage the increase rejection of positively charged solutes and the decreased rejection of negatively charged solutes. Calculated rejection percentages were determined based on instantaneous samples over a single batch and hence could explain the variation observed at different time points.

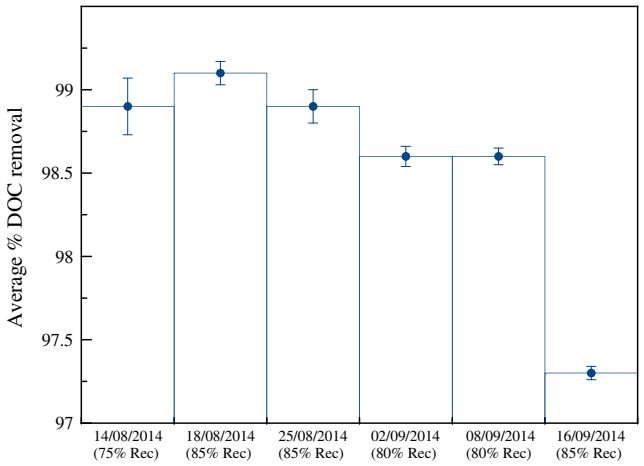

Fig. 5. Average % DOC removal in a batch during batch recovery setting period. Error bars indicate the variation in % DOC removal during different times within a single sampled batch.

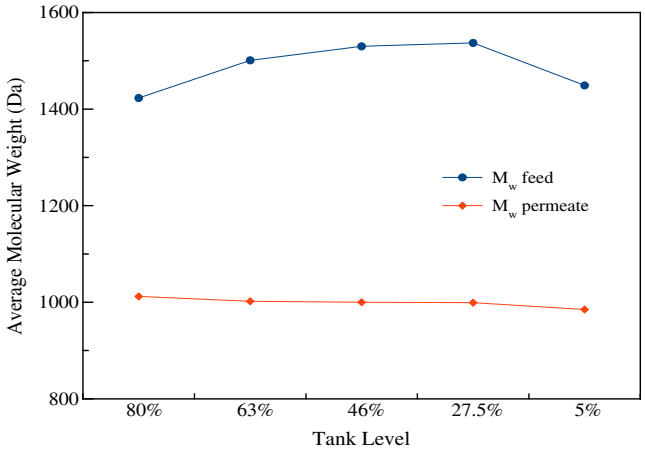

Fig. 4. Average molecular weight of stream components in feed and permeate at sample points during batch.

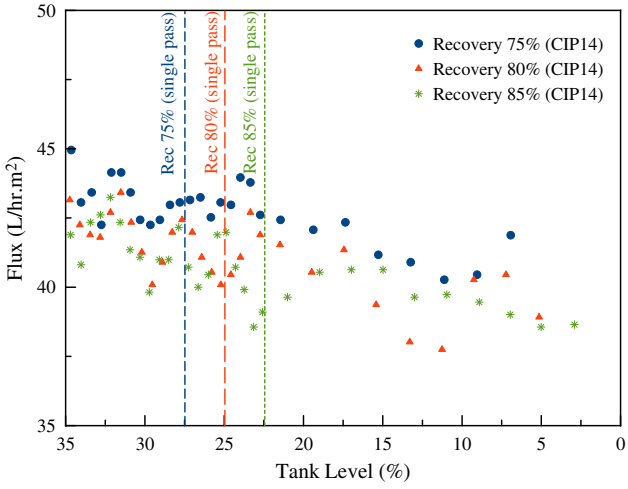

Fig. 6. Flux change with respect to tank volume level for varying overall recovery percentage.

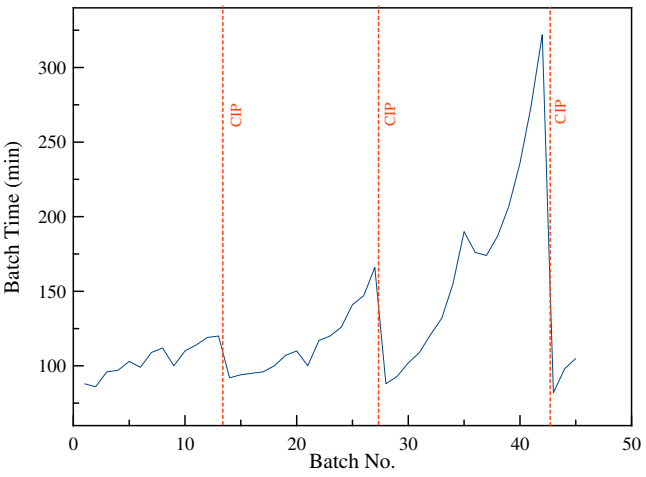

Fig. 7. Summary of batch times over three cleaning cycles at 75% batch recovery.

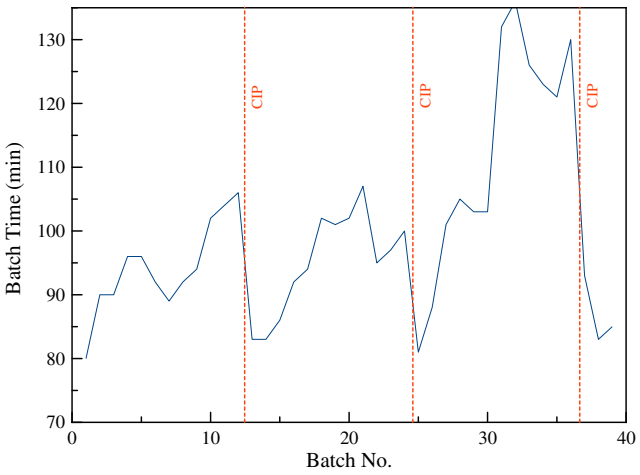

Fig. 9. Summary of batch times over three cleaning cycles at 80% batch recovery.

3.3. Organics analysis of VSEP streams

3.3.1. DOC concentration over the course of a single batch

Feed and permeate samples collected at the beginning and end of a batch process were analysed in terms of bulk organics for a single run (as shown in Table 5). The table demonstrates the typical increase in DOC seen in the feed due to recycling and the resulting increase of DOC concentration in the permeate due to declining flux towards the end of the batch.

Feed and permeate streams were sampled at different points in a single batch cycle to determine the change in DOC concentration. Sample was performed over a 1 month period with 3 different recovery settings explored.

Fig. 3(a) shows that initial feed DOC concentration starts at roughly 6000 mg/L and progressively becomes more concentrated via the recycle mode. At the switch to single pass mode (22.5–27.5%), the DOC concentration of the feed reaches a maximum. In 5 of the 6 batches sampled, the final DOC concentration of the feed is between 15,000–20,000 mg/L, three times the initial concentration. The batch on 14th August (75% recovery) had lower initial DOC concentration which resulted in lower final DOC concentration. Permeate DOC concentration follows a similar trend, as shown in Fig. 3(b). Initial permeate generated has a DOC concentration of roughly 100 mg/L and reaches 250 mg/L by the end of the cycle.

3.3.2. Molecular weight distribution of DOC in the feed and permeate streams

The feed and permeate streams at the sampled time points were also analysed in terms of molecular weight distribution. A weight average molecular weight (M_w) in Dalton was determined at each point and compared in Fig. 4. Previous SUVA analysis showed that the molecular weight distribution in each individual stream did not vary as tank level decreased, as shown in Fig. SI-1(a) & (b). However comparing the feed and permeate streams, the average molecular weight in the permeate is roughly 400–500 Da lower than that in the feed stream which suggests that the NF membrane is rejecting a majority of organics above 1000 Da (see Fig. 5 for values). The nominal molecular weight cut-off for NF membranes ranged between 200–1000 Da [29]. Results indicate that the installed NF membrane is operating at the high end threshold, hence only rejecting organics of higher molecular weight.

3.3.3. The effect of batch recovery on DOC removal

The percent DOC removal achieved by the VSEP unit was explored through the changing of batch recovery percentage. Recovery settings of 75, 80 and 85% were analysed. Each setting was run for two weeks, ensuring that stable operation was obtained. As can be seen in Fig. 5, the difference in DOC removal between the 75% setting (27.5% recirculation set point), 85% setting (22.5% recirculation set point) and 80% recovery setting (25% recovery set point) is minimal. For all cases, a DOC

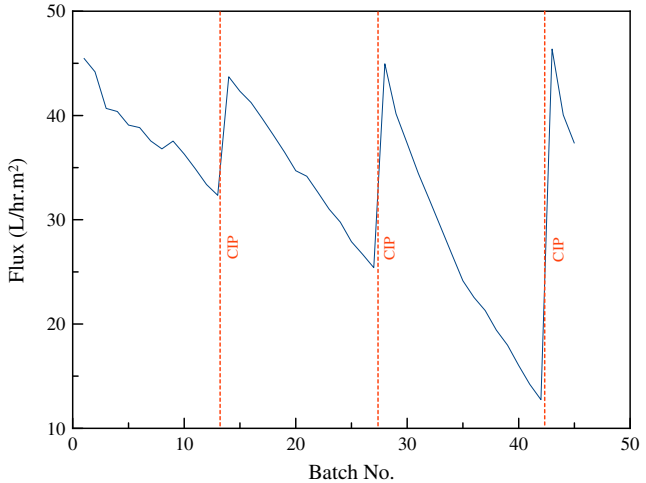

Fig. 8. Summary of average flux over three cleaning cycles at 75% batch recovery.

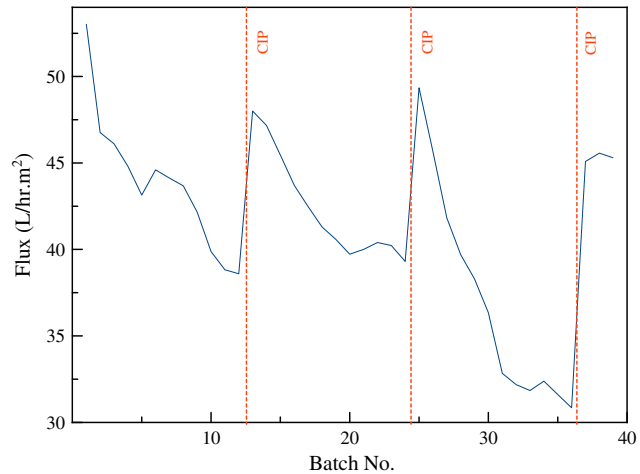

Fig. 10. Summary of average flux over three cleaning cycles at 80% batch recovery.

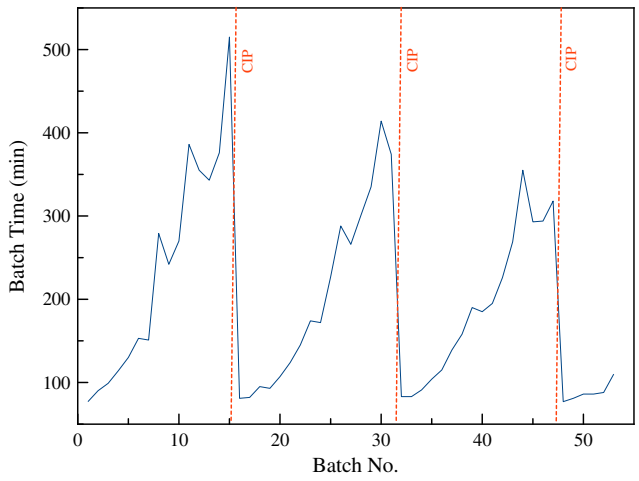

Fig. 11. Summary of batch times over three cleaning cycles at 85% batch recovery.

removal of above 97% is observed. The final tested batch (16/09/2014 — 85% recovery) showed a lower DOC % recovery as the cleaning settings were changed.

3.4. The effect of percentage recovery change on permeate flux

Fig. 6 shows the effect of changing the overall recovery percentage of the system on the permeate flux. Data used to generate Fig. 6 was produced by averaging batch results collected for each recovery setting. There was no notable trend observed when comparing the permeate flux with increasing percentage recovery. Different starting values of permeate flux existed between each of the batches and this was largely due to the MIEX waste starting with different characteristics. More importantly, the reduction in permeate flux appeared consistent between all cases. All cases experienced roughly a 20–30% decline in permeate flux over the course of the batch.

3.5. The effect of cleaning frequency on batch time and flux

Performance of the system was explored over 3 cleaning cycles to determine whether the proposed cleaning in place (CIP) frequency installed at Wanneroo was ideal. This was explored for batch recovery settings of 75%, 80% and 85%. Cleaning frequency was set at every 14 batches.

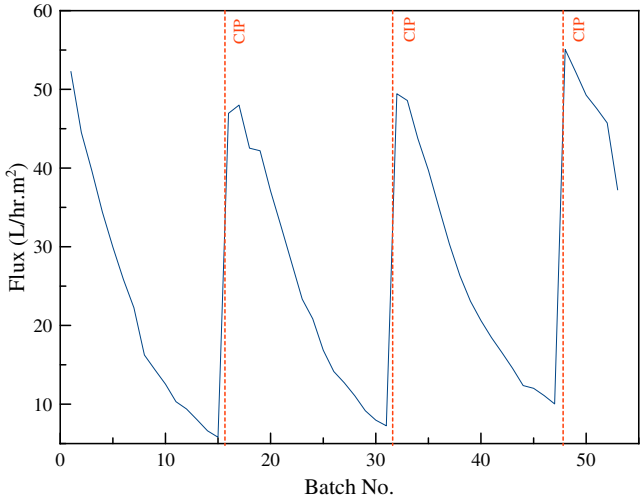

Fig. 12. Summary of average flux over three cleaning cycles at 85% batch recovery.

The first batch occurred directly after a cleaning. Notably the time taken for a single batch began at roughly 80–85 min. In all cases, the batch time after each run increases sequentially with each batch. The first cycle ends at the 14th batch which follows with a thorough cleaning of the lines and the membrane system. After the clean, the following batch returns to 80–85 time duration. Notably at each progressive cleaning cycle, there was an increase in final batch time prior to cleaning (see Fig. 7). It is possible that the progressive use of the membrane has resulted in membrane wearing. However as the batch times always returned to similar durations after each cleaning, it was more likely that the VSEP feed/MIEX waste entering the system was more concentrated than that previously processed.

Fig. 8 shows the average flux measured over an entire batch for the batches represented in the 75% batch recovery setting. The graph is inversely proportional to that observed in Fig. 7. Higher average flux resulted in shorter batch times and lower flux resulted in extended durations. Similarly, the routine cleaning of every 14 batches resulted in the system returning to approximately the same flux 45–46 $L/h \cdot m^2$. Flux appears to decline after each subsequent CIP cycle that suggests the existence of an internal problem such as the build-up of foulants in the system. However the study only focussed on 3 CIP and the general trend of flux between CIP cycles could be variant.

Similar to performance at 75% batch recovery, the initial batch time after a cleaning took between the expected 80–85 min (see Fig. 9). Comparatively, one should see increased batch times as higher recovery would represent longer duration of filtration. Aside from the 3rd cycle at 75% recovery test conditions, this was shown to be the case. It is possible that the order in which VSEP performance was tested (80%, 75% and 85%) may have influenced batch times. Under 80% batch recovery, the batch continued to increase with batch number over 10 batches then plateaus for the remaining few batches. The third cleaning cycle did experience extended batch times but followed the same general trend.

The average flux for each batch reflected the batch times (see Fig. 10). Average flux decreased in the early batches following the clean and then began to flatten out. Notably the flux always returned to 45–50 $L/h \cdot m^2$ after thorough cleaning in all cases. As average flux and batch time patterns did not significantly change these three cleaning cycles, it is possible that operation of VSEP at 80% batch recovery and 14 CIP is adequate.

The batch times experienced in the 85% batch recovery operation scheme were significantly higher than that seen previously (see Fig. 11). It is highly possible that the process MIEX waste had a change in characteristic between the tested settings. Consistent with previous analysis was the batch time directly after a clean. Sequential batches experienced a steep increase in batch duration and unlike the pattern seen in 80% batch recovery, no plateau was observed prior to cleaning commencement. Final batch times prior to cleaning reach above 300 min with a maximum batch time seen at 515 min. Extended exposure of the NF membrane to high concentration feed can affect the performance of the membrane in the long run. It is ideal to increase the CIP frequency if one seeks to operate at 85% batch recovery in order to protect the functionality of the membrane.

Despite the higher organic content of the VSEP feed, initial average batch flux remains largely unchanged between settings. However the degree of decline in flux is much more significant in the 85% recovery setting. Comparing the average flux experienced in the first batch after a clean to the batch prior to a clean, approximately an 80–85% decline in average flux was observed. This further details the need to increase the CIP frequency to a more acceptable value (Fig. 12).

3.6. The effect of pH, temperature and transmembrane pressure on batch performance

Other parameters such as pH, temperature and their effect on batch performance were also explored. These results can be found in Fig. SI-2.

Results indicated that pH had no significant influence on batch performance in terms of average flux. Temperature was shown to increase over the duration of the batch. However it is likely that the increase was due to the recirculation of the feed through the VSEP filter pack during the longer batch times. As the operation of the VSEP unit is in constant pressure and varying flux, the calculated transmembrane pressures remaining fairly constant over the duration of batches and hence had no influence on the performance.

3.7. Major benefits of VSEP installation at Wanneroo GWTP

Early operation of VSEP to treat MIEX waste has resulted in a substantial reduction of salt intake at the plant. In the first 8 months alone, the ability to re-use the high concentration salt permeate has allowed for a 38% reduction in salt costs. Additionally savings have been evident in terms of waste disposal. By operating the VSEP at 75–85% recovery, a substantial volume of MIEX waste is recycled instead of being sent to waste. In terms of operation, the key operating cost is the need for chemical dosage, however the savings made in salt intake and waste disposal outweigh the operating costs and is likely to reap savings over the project lifecycle.

4. Conclusions

The VSEP system unit implemented at Wanneroo groundwater treatment plant has been utilised to successfully treat waste produced from the MIEX regeneration process. In all cases, over 97% of the dissolved organic carbon in the MIEX waste was removed. Characterisation of collected samples indicates that the system removed a majority of divalent ions but is less selective towards monovalent and uncharged ions. Furthermore, organic characterisation of the permeate and feed streams showed that the permeate consisted of organics that were 400 Da smaller in average molecular weight than that observed in the feed.

Changing the overall permeate recovery of the system between 75%, 80% and 85% exhibited no significant changes in performance. Exploration of batches in a collective sequence indicated a significant deterioration in flux as well as an extension in batch times for batches prior to chemical cleaning. Increasing the frequency of chemical cleaning could improve the overall performance of the system, reduce the time of operation and protect the membrane installed in the unit.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.desal.2015.02.042.

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