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Use of vibratory shear enhanced processing to treat magnetic ion exchange concentrate: A techno-economic analysis

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HIGHLIGHTS

- Vibratory shear enhanced processing has been used to treat MIEX concentrate.
- 97% dissolved organic compound removal, and 80% recovery of waste as permeate
- Major savings achieved on salt consumption and waste disposal
- A payback period of 6–7 years is estimated.

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ABSTRACT

Disposal of waste generated by inland water treatment technologies is highly expensive. The introduction of vibratory shear enhanced processing (VSEP) to treat waste produced from magnetic ion exchange (MIEX) shows benefits in terms of performance and economics. A small VSEP unit fitted with a nanofiltration (NF) membrane is capable of treating up to 15 kL of MIEX waste per day, is able remove more than 97% of dissolved organic compounds as well as recover over 80% of waste in the form of permeate. The reuse of permeate to make-up brine has seen significant reductions in salt consumption and waste disposal at Wanneroo Groundwater Treatment Plant (GWTP). During the first year of VSEP operation, salt consumption reduced by 42% and waste disposal was projected to reduce by 23.9%. Further improvements in both cost categories were observed in the second year of operation and considering the same trend is followed, the payback period of the project will occur between the 6th and 7th year of operation for discounted analysis and has a positive net present value.

1. Introduction

Concentrate management is a significant financial burden across all industries that generate water based wastes. Concentrates can be characterised in terms of concentration, organic content, pH, turbidity, toxicity among other parameters. In any start-up project, concentrate management should be a major consideration and can contribute significantly towards the operating costs.

Vibratory Shear Enhanced Processing (VSEP) is a technology which applies torsional vibration to a membrane to increase separation and reduce fouling of a membrane. High shear rates at the membrane surface allow solids and foulants to lift off the membrane surface (Fig. 1). Suspended colloids are washed away at the same rate as new particles that arrive [1]. Dependant on the pressure applied and the filtration rate, the suspension layer thickness can vary. VSEP has been successfully applied in industries ranging from medical, latex concentration, acid clarification, pigment washing and treating groundwater. The high shear process exposes membrane pores for maximum throughput, reaching rates of the order (1–3) × 10^5 s^{-1} [2].

VSEP was used to treat waste generated from a magnetic ion exchange (MIEX) process at the Wanneroo GWTP, Western Australia. MIEX is a technology that uses magnetic beads to remove dissolved organic compounds from groundwater [4]. Resin particles are 150–180 μm, macroporous and contain a magnetized component that allows them to act as weak magnets [5]. The MIEX resin used in this process can be readily regenerated by mixing with high concentrated brine. Within the regeneration phase, waste with high concentrations of salt and organics are produced [6].

Membranes ranging from microfiltration, ultrafiltration, nanofiltration and reverse osmosis have all been considered for use with VSEP [7]. Typically a plate and frame configuration is used in most setups. The setup at Wanneroo incorporates a DOWTech NF-270 membrane in

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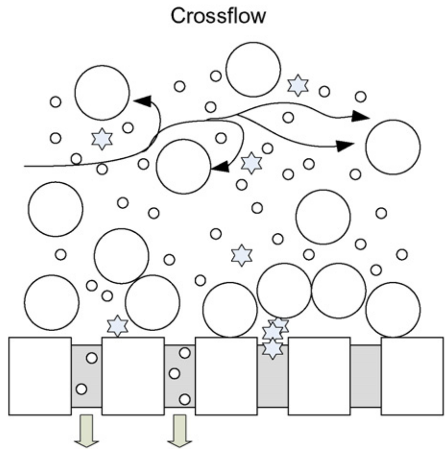

Fig. 1. The difference in colloid aggregation in cross flow filtration and VSEP. Image adapted from Johnson [3].

the filter pack. Previous studies have shown that VSEP units convert up to 99% of total shaft energy into shear that acts upon the membrane. This is significantly higher than the 10% conversion offered in conventional cross-flow filtration systems [8].

Although it is comparatively energy efficient, VSEP is recommended for operations dealing with larger volumes. Regardless of the capacity, the same mechanism of shear generation is performed. In cases of low volumes, a significant amount of excess energy may be applied into driving the motor shaft. In addition, the durations required for start-up operation, filtration and cleaning will remain the same regardless of volume and will consequently result in higher than necessary operating costs [9].

A range of economic analysis has been performed on membrane processes in the past. A study by Owen performed an economic assessment for the treatment of waste water via membrane processes. Results from extensive pilot plant trials of UF and MF membranes determined that the most significant factors to overall cost were membrane cost, membrane replacement frequency and power [10]. The author does not account for additional costs associated with disposal of chemicals though states that treatability of chemicals will be major consideration when selecting a treatment process.

A model devised by Sethi et al., determined that the overall economics of crossflow UF and UF processes were associated with raw water quality and resultant permeate flux. Treatment costs were predicted to have relatively lower economies of scale when permeate flux was limited by concentration polarization and cake growth [11]. The VSEP project is dealing with concentrated MIEX waste so it is likely to influence the degree of permeate flux. However the vibrational movements during filtration should minimise the effects of concentration polarization.

Another economic analysis on treatment of waste water in a full scale UF plant focussed on determining the sensitivity of total operating cost to changes in total output, filtration time and filtration flux. It was found that changes in the permeate output and filtration flux have a significant effect on operating cost [12]. A similar operation was observed in our study where lower filtration flux extended batch times and hence influenced the utilities usage during operation. Permeate output could be altered by changing the overall recovery of the VSEP system but is expected to have less significant influence on operating costs as the changes between settings were small (75, 80 and 85% permeate recovery).

Pilot studies involving the treatment of surface water and groundwater using UF and NF membrane processes have yielded results that estimated permeate costs of $\$0.15–0.25/m^3$ [13–16]. It is difficult however to make a direct comparison to this study as the system boundary developed in the performance does not include the initial treatment of groundwater via MIEX.

A case study exploring the treatment of concentrate generated from a proposed recycled water facility involved VSEP installation in a multiple system treatment. The pilot scale unit was operated for 4 months and determined that the optimal concentrate recovery achieved was 85%. Higher recoveries could be obtained but lower flux rates and higher feed pressure requirements influenced the operation [17].

The economic analysis determined that capital costs included equipment, installation, the SCADA control system, hoist crane hire and labor. Operation and maintenance costs included acid for feed conditioning, membrane replacement along with general utilities and labor costs [18]. The study demonstrated that multiple system designs which incorporated VSEP were significantly cheaper in terms of capital cost than systems incorporating evaporation ponds (seen in Table 1).

Despite several publications based on the economic analysis of membrane processes, they are mostly outdated and are too broad to be comparable with a process like VSEP. Aside from the study in Big Bear Valley, there has been no other economic based case study that has focussed primarily on VSEP as an emerging technology in an industrial sized setting.

VSEP was introduced in process at Wanneroo GWTP. The key streams entering the system boundaries are the MIEX regeneration

Table 1
The calculated life cycle costs for multiple system design scenarios in Big Bear Valley (adapted from Lozier, in 2007 USD) [17].

Design scenarios	Capital cost ($USD)	Annual O&M cost ($USD)	Life cycle costs ($USD)
Evaporation pond only + flow conveyance + evaporation pond	$13,106,000	$342,000	$18,613,000
VSEP + flow conveyance + evaporation pond	$6,169,000	$491,000	$14,075,000
Effluent mixing + VSEP + flow conveyance + evaporation pond	$6,199,000	$450,000	$13,444,000
EMS + flow conveyance + evaporation ponds	$9,206,000	$514,000	$17,482,000
EDR + flow conveyance + wetlands	$6,896,000	$514,000	$15,172,000
VSEP + flow conveyance + wetlands	$6,067,000	$483,000	$13,844,000
Effluent mixing + VSEP + flow conveyance + wetlands	$5,820,000	$433,000	$12,792,000

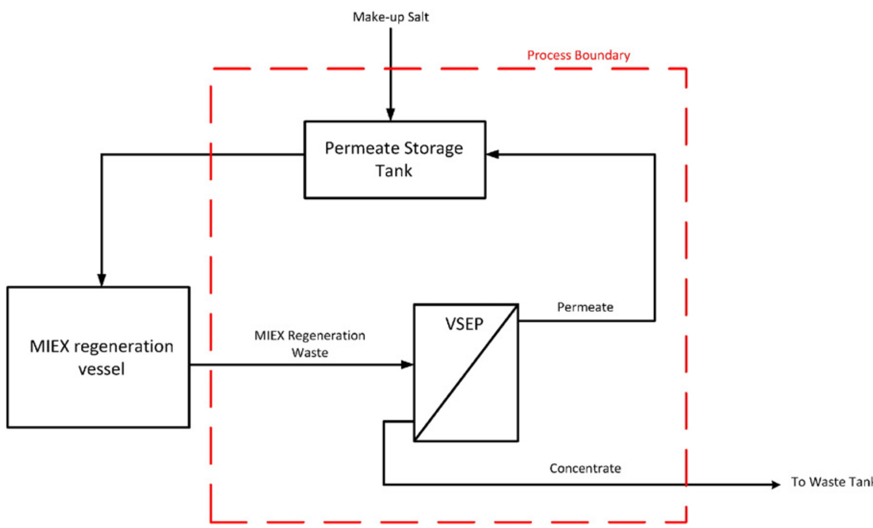

Fig. 2. A process flow diagram showing the system boundary of the installed VSEP established to conduct the economic analysis.

waste which is treated via the VSEP system and the make-up salt required to generate the brine medium for MIEX resin regeneration. The two streams that leave the system are the VSEP permeate that has been further processed with make-up salt and the concentrate produced by VSEP that is sent to the waste tank for tankerage (Fig. 2).

The following paper evaluates the economic benefits of the installation of VSEP to treat MIEX waste at Wanneroo GWTP. The influence of flows crossing the system boundary plays a substantial role in the determination of financial costs associated with process operation.

2. Materials and methods

2.1. Materials

The VSEP unit was installed at Wanneroo GWTP. The plant is located approximately 25 km north of Perth in Western Australia (−31.722871, 115.852915). The VSEP filter was installed in pilot model (P-mode), a configuration composed of more membranes than when conducted in laboratory mode (L-mode) and is manufactured by New Logic International (USA).

The VSEP equipment consists of multiple structures. Firstly, the filter pack unit is fitted with the membrane and consists of the torsion spring and beatings. The other structure is the motor shaft that drives the movement of the filter pack (See Fig. 3). A simple VSEP system has a footprint of 1.85 m^2 and can accommodate 17.187 m^2 of membrane area [19].

Additionally tanks that hold feed and generated permeate are required as part of the VSEP system. Depending on the capacity of the VSEP unit, the sizing of these reservoirs may be different. In this study, the feed tank can hold up to 500 kL of MIEX waste and the permeate tank was discharged to a pre-existing storage tank. Furthermore supplementary equipment that contributes to capital includes the process logic control (PLC) system for data measurements, online measurement instruments including flow meters and pH monitors, piping and pumps.

The SCADA control system used allowed for access to minute interval operational data to be collated and used to predict operating costs at varying recovery settings. Additionally, financial reports at Wanneroo GWTP were compiled on a monthly basis and the values were used to generate life cycle projections.

2.2. Method of process operation

In a typical batch cycle, the empty tank is filled to 82.5% volume with the MIEX concentrate. 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 final tank level is governed by

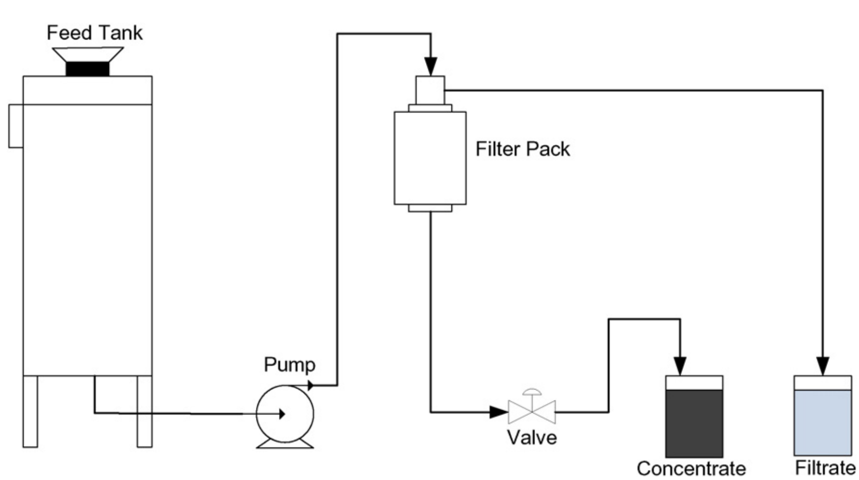

Fig. 3. The basic VSEP system setup.
Imaged adapted from Culkin.

the desired batch recovery percentage. When tank level drops below 22.5–27.5%, the system switches into single pass mode via an automated valve and the concentrate stream flows directly to the waste tank. This mode of operation continues until the tank level reaches its minimal threshold of 5% and the filtration ceases. The remaining contents are drained into the same waste tank and the vessel is flushed with process water prior to the next batch [20].

2.3. Cleaning in process (CIP)

During chemical cleaning, hydrex 4703 (acidic) is fed throughout the system to clean the lines and the filter pack. Following the washing, the filter is flushed with Hydrex 4705 (alkaline) which follows with a general flush with process water.

2.4. Technical performance

Operation of VSEP at set permeate recoveries of 75–85% all resulted in over 98% removal of dissolved organic carbon [20]. Molecular weight distribution analysis between the feed and permeate streams showed that the average molecular weight seen in the feed is 1400–1500 Da compared to just 1000 Da in the permeate. Additionally, the rejection studies during the course of the batch showed that the fitted NF-270 membrane was particularly efficient at rejecting solutes with multivalent charge (>70% rejection) and to a lesser extent monovalent ions such as sodium and chloride (10–20%).

Frequency of cleaning was determined to have a significant impact of membrane performance, in particular the permeate flux and batch duration. Frequency settings of 14 batches and 16 batches between cleaning were explored. The decline in flux in NF membrane is likely to be associated with the concentration of feed and scaling. A similar observation relating favored adsorption of high polarity components in solution was identified in past tests involving NF membranes [21].

3. Results

3.1. Economic performance results

3.1.1. Assumptions

To conduct economic analysis of the project, some key assumptions were made.

- Project life cycle: 10 years (The implementation of VSEP at Wanneroo GWTP is intended for long term use).
- There is no cost associated with feedstock as it is a by-product of the existing MIEX regeneration process.
- Previously unused storage tanks were allocated to becoming VSEP feed tanks and permeate tanks and hence did not contribute to the capital cost.
- The plant undergoes 1 month of annual shutdown per year which incorporates maintenance and downtime. Estimated availability of the plant per year is 310 days (85%)

3.1.2. Capital cost

Capital cost of VSEP installation was provided by IXOM Australia. Costs associated with this figure include the VSEP unit, supporting base, the SCADA control unit, membrane, piping, online instruments, installation and delivery costs and the external shelter (seen in Table 2).

3.1.3. Operating cost in first year of operation

Operating costs were provided by the plant operators. Key items contributing to operation costs include:

- Process water: required to flush the system between batches, also used during forced shutdown and routine CIP performance.
- Electricity: required to operate many of the moving parts in the system with the pumps and the motor shaft being the major contributions to power usage.
- Chemicals: Such as Hydrex 4703 and Hydrex 4705. They are currently used every 14–16 batches during routine CIP.
- Labor: during commencement phase, one project manager and one operator was allocated to maintain the performance of the VSEP system. However once trial phase operation was in place, one operator was allocated to the trial as a part time resource. The Total full time equivalent (FTE) operational workload was expected to be in the order of 0.05 FTE.
- Maintenance: maintenance can include fixing leaks, monthly torque tension check, changing membranes.
- Salt consumption: defined as the total amount of salt ordered on-site for the MIEX resin regeneration. (Note: salt is not required for VSEP operation).
- Waste disposal & transport: defined as the total amount of waste to be removed from Wanneroo GWTP.

Table 2
Table comparing the capital costs of the VSEP system to the system pre-installation where 'n.a' stands for non-applicable.

CAPEX		
Item	VSEP	PRE-VSEP
VSEP module	$300,000	n.a
Engineering, infrastructure	$200,000	n.a
Total	$500,000	0

The base case operating costs are considered for the MIEX unit alone. Key items from MIEX operation that are influenced by VSEP installation are salt consumption and waste disposal and transport. The alternative, which incorporates the VSEP unit, is the combined MIEX and VSEP case Table 3. captures the expected annual operating costs with running the VSEP unit but also shows the savings that are realised as salt consumption is decreased and waste disposal and transport is also decreased, as a result of the volume reduction achieved. To generate the graph, the following points were assumed:

- Feed pressure is constant.
- Starting tank volume is the same regardless of recovery setting.
- Process water usage is directly proportionate to volume of waste treated.
- The average VSEP recovery was 80%.

Consistent with literature, operation of VSEP on low recoveries does not generate enough savings to warrant the installation [9]. Furthermore, the need for a plant operator during operation contributes towards the overall OPEX cost. It is beyond 18% permeate recovery that the overall cost benefits of VSEP operation becomes evident (see Fig. 4). Although increased recovery results in higher use of electricity, process water and cleaning chemicals, the reductions in salt consumption by the MIEX and the reduced amount of waste to be disposed are

Table 3
Table comparing the operating costs of the VSEP system to the system pre-installation (Treated MIEX waste 2790 kL/year).

Items	VSEP		Pre-VSEP	
	Cost	Units	Cost	Units
Process water	$817	$/year		
Electricity	$195	$/year		
Chemicals	$30,915	$/year		
Labor	$13,818	$/year		
Maintenance	$223	$/year		
Salt consumption	$83,538	$/year	$144,153	$/year
Waste disposal & transport	$133,962	$/year	$175,953	$/year
Total	$263,468	$/year	$320,106	$/year

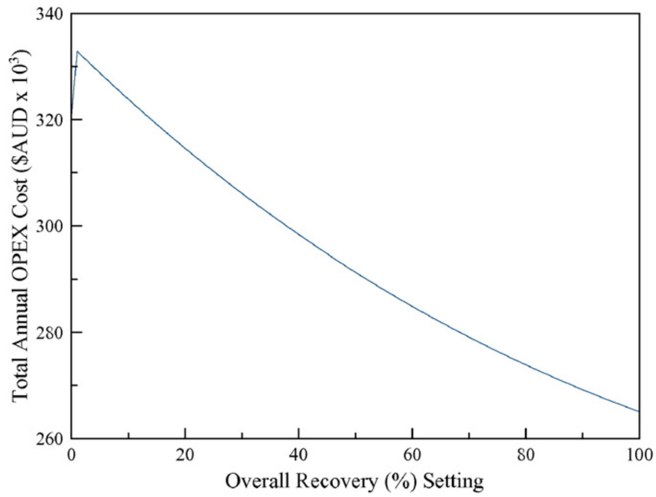

Fig. 4. Operating cost of VSEP with respect to increasing overall recovery setting.

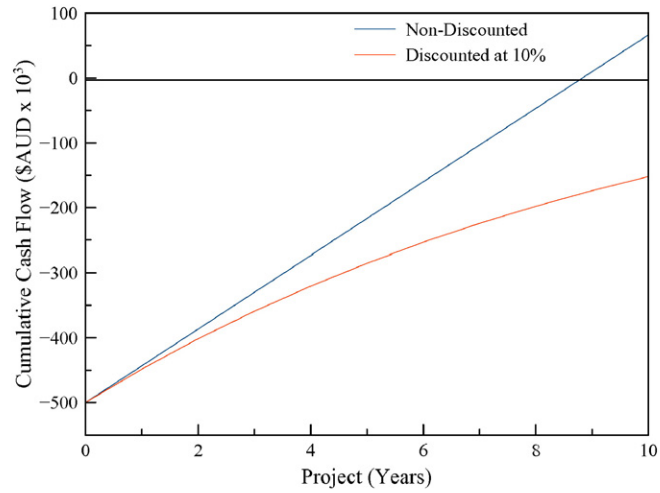

Fig. 5. Cumulative cash flow of VSEP operation on MIEX waste projected over duration of project life cycle.

more influential on OPEX cost. Increasing the volume of MIEX waste treated could lead to higher savings, however the operation is limited by the facilities ability to store permeate generated by the VSEP. It should be noted that operation beyond 90% is unrealistic and to reach this values, additional recovery steps such as downstream desalination would need to be implemented.

VSEP annual savings with respect to system dependency on

- Concentrate vs permeate

The ratio of concentrate and permeate production is likely to play some effect in VSEP based annual savings. Ideally, one would prefer the majority of the brine content from the feed to be kept in the permeate in order to minimise the volume of concentrate waste that is required to be disposed. This was performed via increasing the overall system recovery and was shown to reduce disposal costs (see Fig. 4).

- Capacity of VSEP

Currently at Wanneroo GWTP, the VSEP capacity has not been reached. Larger volumes however are likely to result in increased savings as VSEP has previously been shown to be more economically viable when dealing with larger volumes.

- Supply of brine

At Wanneroo GWTP, waste from the MIEX process is held in a storage tank before it is fed through the VSEP. The supply of the brine at Wanneroo is greater enough to meet the capacity of VSEP operation but is not in practice.

- Demand for permeate

The reason why VSEP is not operating at full capacity is largely a result of the demand for permeate at Wanneroo GWTP. The amount of permeate produced by the VSEP exceeds the amount required for the resin regeneration step. Excess permeate is currently held in a storage tank, however there is an action to treat excess permeate via wind aided intensified evaporation (WAIV).

3.1.4. Life cycle projections

Fig. 5 shows the projected cumulative cash flow during the life cycle of the VSEP operation. Key assumptions include:

- Project life cycle of 10 years
- Discount rate is 10% (value was selected to adjust for risks and associated opportunity costs. Additionally a discount rate of 10% of most stable in start-up projects)
- The current settings of operation are followed over the course of the life cycle i.e. same cash flow each operating year.

The projection curve indicates that the cash flow value at the end of the project of $66,380 with pay-back occurring 8 years and 10 months after commencement of VSEP use for non-discounted analysis (see Fig. 5). Taking 10% discount rate, the project finishes with a net present value of — $151,984. The calculated internal rate of return was 2.33%. Based upon first year projections, the installation of VSEP is unlikely to see a positive present value in the given operating cycle.

3.1.4.1. Comparison with past operation over the period 2010–2014. Between the years, 2010–2013, salt intake costs increased from $95,000 AUD to $144,153 AUD (see Fig. 6). The increase in annual cost is largely due to price inflation and increased consumption due to increased groundwater treatment capacity of the plant. The VSEP unit installation was completed in September 2013 allowing for 8 complete months of VSEP operation in the 2013–14 financial year. During the financial year, the cost of salt intake decreased to $90,000 AUD, a 38% reduction in cost compared to the previous year. It is possible to further decrease the salt intake costs. Projection of the 8 months of VSEP over an entire year results in an estimated annual salt cost of $83,538 AUD, a 42% reduction.

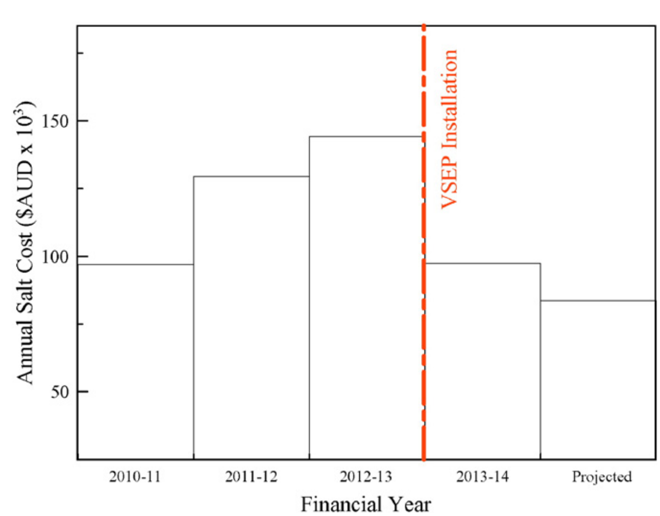

Fig. 6. The annual cost of salt intake during the period 2010–2014 and the projected cost of 2014–2015 based on current data.

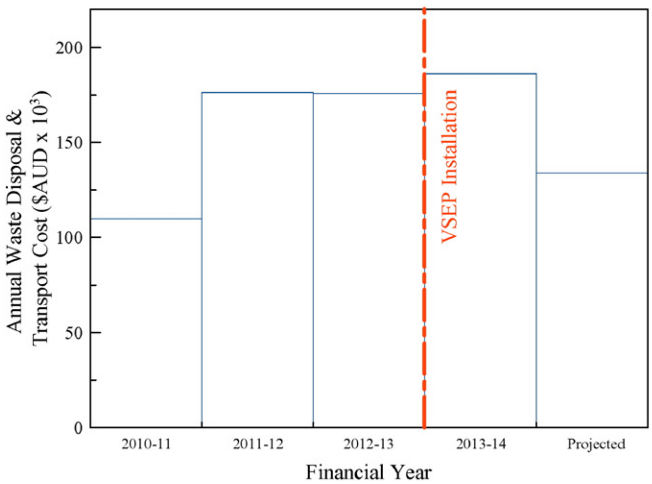

Fig. 7. The annual cost of waste disposal and transport during the period 2010–2014 and the projected cost of 2014–15 based on current data.

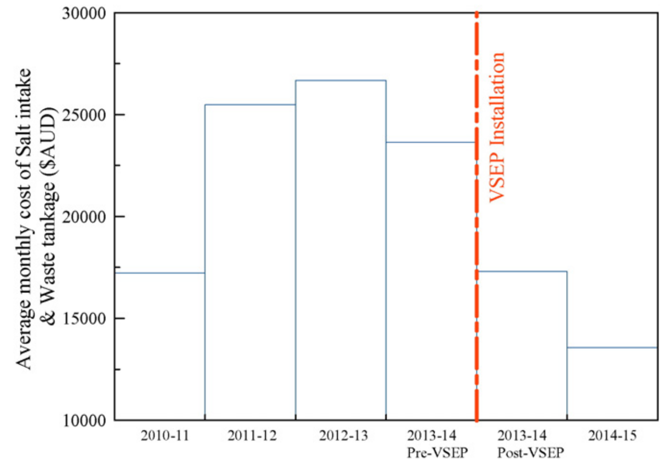

Fig. 8. The average monthly cost of salt and waste disposal during the period prior and post-VSEP installation.

Similar trends can also be seen in waste disposal and transport at Wanneroo GWTP during the course of the past 4 financial years (Fig. 7). Interestingly, the most recent financial year (2013–2014) has a waste disposal cost higher than those previously despite the installation of VSEP. However a significant proportion of those tankerage costs occurred during the previous months prior to VSEP installation. The projection bar representing the projected costs of waste disposal post-VSEP installation provides an indication of the savings of waste disposal. Compared to the costs in 2012–2013, a projected drop of 23.9% in disposal cost is expected.

3.1.4.2. Average monthly expenses associated with VSEP installation. Fig. 8 shows the average monthly cost ($AUD) for intake salt and waste tankage at Wanneroo in the past 5 operational years of operation. The peak cumulative cost occurred in the operating year of 2012–2013. VSEP was installed at Wanneroo during the 2013–2014 which saw noticeable reduction in costs by 35.1% during the 8 months of operation. With VSEP in continuous operation, associated costs of salt and waste further reduced to approximately $13,500 each month. Compared to the baseline (2012–13), a reduction of 49.2% has been observed. The improvements in associated costs during the VSEP operation years 2013–14 and 2014–15 are likely due to significant improvements in number of commissioning and research related activities. During the first year of operation, the MIEX regeneration system suffered from a broken header resulting in higher than normal resin wastage through to the waste brine. Collectively this prevented the VSEP system from running optimally in 2013–14.

3.1.4.3. Projected life cycle change after 2 years of operation.

Items	VSEP		Pre-VSEP	
	Cost	Units	Cost	Units
Process water	$899	$/year		
Electricity	$215	$/year		
Chemicals	$34,006	$/year		
Labor	$3300	$/year		
Maintenance	$245	$/year		
Salt consumption				
Waste disposal & transport	$162,612	$/year	$320,106	$/year
Total	$201,777	$/year	$320,106	$/year

Comparatively, the second year of operation resulted in an even more significant reduction in salt consumption and waste disposal costs. The overall operational costs in the second year of operation are 33.2% less than that observed at the baseline. This saving can also be reflected on the life cycle projection curve.

The projection curve indicates that the cash flow value at the end of the project of $621,599 with pay-back occurring 5 years and 9 months after commencement of VSEP use for non-discounted analysis (see Fig. 9). Taking 10% discount rate, the project has a payback time 6 years and 8 months and finished with a net present value of $170,998. The calculated internal rate of return was 16.90%.

4. Conclusions

Installation of VSEP to treat MIEX waste at Wanneroo GWTP has already shown significant economic savings. During the first year of operation at 80% volumetric capacity, there has been up to $57,000 AUD saving in terms of salt consumption, waste disposal and transport. The amount of salt consumption and waste disposal has reduced by 42% and 23.9% respectively in comparison to the year prior to VSEP installation. Increasing the volume of waste treated could result in further economic improvements. Cumulative cash flow based upon first year savings indicates that the project has will not reach the net positive payback in the recommended project life cycle. However, projections based on results from the second year of operation indicate that faster payback period of 6 years and 8 months as well as a positive net present value of $170,998 AUD.

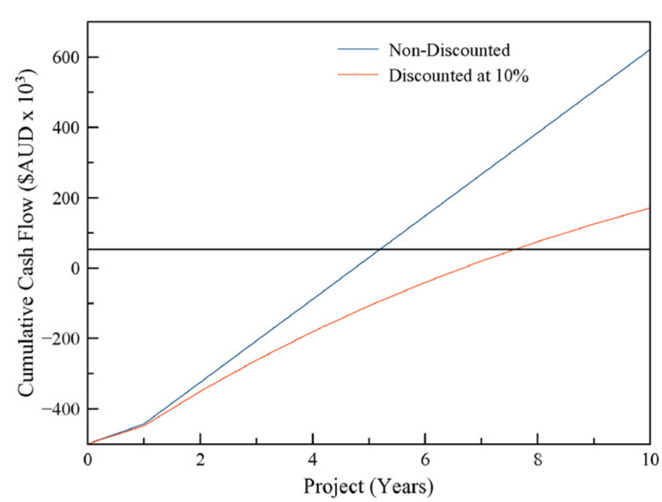

Fig. 9. Cumulative cash flow of VSEP operation on MIEX waste projected over duration of project life cycle using values obtained after 2 years of operation.

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