

Desalination of oil sands process-affected water and basal depressurization water in Fort McMurray, Alberta, Canada: application of electrodialysis

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ABSTRACT

The high content of inorganic species in water used to extract bitumen from the Alberta oil sands and in the groundwater below the oil sands is an increasing environmental concern. These water matrices require treatment before they can be reused or safely discharged. Desalination of the oil sands process-affected water (OSPW) and groundwater, or basal depressurization water (BDW), can be accomplished with deionization techniques such as electrodialysis (ED). In order to achieve the effective ED treatment, OSPW and BDW were pretreated with coagulation–flocculation–sedimentation to remove solid species and turbidity. We demonstrated that a conductivity range for industrial reuse of OSPW and BDW can be achieved with the ED treatment and showed the possibility of applying ED in the oil sands industry. A continuous ED system that reuses the diluate stream as a source for the concentrate stream was designed. The cost of a hypothetical ED water treatment plant in Fort McMurray, Alberta, was estimated to be C\$10.71 per cubic meter of treated water.

Key words | basal depressurization water, deionization, electrodialysis, oil sands process-affected water, water reuse

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INTRODUCTION

It is estimated that the oil sands in Northern Alberta, Canada, contain over 1.6 trillion barrels of heavy crude oil called bitumen (NEB 2006). The oil sands play an increasingly important role in world energy markets, and the Canadian government is closely working with industry to develop this resource in order to produce a reliable energy source for the future. Canadian companies are investigating innovative ways to harvest bitumen from the Alberta oil sands (Martin *et al.* 2010; Gamal El-Din *et al.* 2011), but the current hydro-transportation process used to extract bitumen from the oil sands requires large quantities of water and incurs an environmental risk. For each barrel of oil produced from the oil sands, at least three barrels of fresh water must be imported from Athabasca River (Allen 2008a), and most of this water becomes contaminated after the bitumen extraction process. The oil sands process-affected water (OSPW) contains toxic organic acids such as naphthenic acids and inorganic species in the concentration range that is characteristic for slightly brackish water. Further, the groundwater, or basal depressurization water (BDW), beneath the oil sands also contains high quantities of inorganic ions such as sodium, chloride and compounds which constitute total

alkalinity (Allen 2008b). In the open pit mining, the depressurization of basal aquifer is commonly practiced in order to reduce the risk of pit wall failure, which produces bulk brackish water that needs to be managed. Efficient and cost-effective methods to remove organic and inorganic components from OSPW and BDW will allow recycling or safe disposal of these waters and reduce the burden on fresh water resources. Researchers are investigating physical, chemical, and biological methods to remove organic and inorganic constituents in OSPW and BDW (Gamal El-Din *et al.* 2011; Kim *et al.* 2011; Pourrezaei *et al.* 2011; Kim *et al.* 2012; Hwang *et al.* 2013).

Electrodialysis (ED), a widely used desalination technology for saline streams, employs selective cation- and anion-permeable membranes under applied voltages to separate ionic species from their aqueous solution (Van Geluwe *et al.* 2011). Typically, during ED, source water is pumped into the ‘diluate’ stream of the unit, and deionized, distilled water is pumped into both ‘diluate’ and ‘concentrate’ streams. The rectifier creates an electric potential across the membranes causing anions to migrate toward the anode and cations to migrate toward the cathode. Anion exchange

membranes (AEM) allow only anions (sulfate, chloride, etc.) to flow into the concentrate stream of the unit while retaining cations in the diluate stream. Cation exchange membranes (CEM) allow cationic contaminants (sodium, potassium, etc.) to pass through the membrane into the concentrate stream (Van der Bruggen *et al.* 2004). The utility of ED technology has not yet been examined in the treatment of oil sands water, although oil sands companies are required to treat oil sands water to minimize its toxic impact on the environment. This study investigated the potential of ED to deionize OSPW and the BDW and evaluated the economics of an ED plant designed for the treatment of oil sands processed water in Fort McMurray, Alberta, Canada.

MATERIALS AND METHODS

Tested water samples and quality

Raw OSPW was collected in January 2010 from the West In-Pit water pumping station at the Syncrude Canada Ltd. site in Fort McMurray, AB, Canada. Raw BDW was collected in January 2010 from the Joslyn North Mine site in Fort McMurray, AB, Canada. Physicochemical properties of the collected samples of OSPW and BDW are described in Table S1 (Supporting Information, available online at <http://www.iwaponline.com/wst/068/533.pdf>).

The average OSPW sample turbidity (70.0 NTU) was significantly higher than the average BDW sample turbidity (1.8 NTU) due to higher concentration of suspended solids in OSPW. The total dissolved solids (TDS) values of the collected OSPW and BDW samples were 3,126 and 16,177 mg/L, respectively. The conductivity, chemical oxygen demand (COD), and acid extractable fraction (AEF) contents were higher in OSPW than in BDW; however, BDW had significantly higher levels of inorganic ions (e.g., sodium and chloride) and total alkalinity than OSPW. OSPW and BDW were preserved in polyvinyl chloride barrel containers and stored at 4 °C in a temperature controlled room. Prior to sampling from the containers, the waters were stirred vigorously with a mechanical mixer for 10 min to homogenize samples. Water samples were warmed to a room temperature (22 ± 1 °C) before the experiments.

Coagulation–flocculation–sedimentation

A jar tester unit with 2-L square jars (Phipps and Bird, Richmond, VA, USA) was used for coagulation–flocculation–sedimentation (CFS) pretreatment of OSPW and BDW

samples. Aluminum sulfate octadecahydrate ($\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$) (Fisher Scientific, Fair Lawn, NJ, USA) was used to coagulate OSPW and BDW samples. The coagulant dose was optimized in our previous study based on the lowest supernatant turbidity after CFS treatment (Pourrezaei *et al.* 2011). The flocculation was enhanced by the addition of cationic polymer, poly-dimethyl diallyl ammonium chloride (poly-DADMAC) (NSF certified, Clear Tech, Saskatoon, SK, Canada). This flocculant was proven to be effective in the CFS treatment of OSPW (Pourrezaei *et al.* 2011). The CFS pretreatment was performed as follows: (i) coagulant (250 mg/L as alum) was injected and the sample was mixed at 120 rpm for 15 s, (ii) poly-DADMAC (5 mg/L) was injected and the rapid mixing was continued for another 15 s, (iii) the sample was mixed at 30 rpm for 10 min, and (iv) the sample was allowed to settle for 2 h. The treated samples were collected through the sampling ports near the bottom of each jar and used as feed water in ED treatment.

Ion exchange membranes and electrodialysis equipment

A HEED® laboratory-scale ED unit (EET Corporation, Harriman, TN, USA) was employed in ED experiments. The system consisted of three hydraulic streams: (i) a ‘diluate’ stream of source water from which ions were transported, (ii) a ‘concentrate’ stream to which ions were transported, and (iii) an ‘electrode’ stream of electrolyte solution to maintain electrically neutral stack solutions. Three tanks (20 L each) and three pumps (Iwaki Magnet Pump; 25.6 gal/min, Iwaki Co. Ltd, Tokyo, Japan) were used to circulate the streams continuously. The circulation flow rate of the concentrate and diluate streams was maintained at 0.342 m³/h (EET-Corporation 2011). The electrolyte solution was sodium sulfate (Na_2SO_4) (Fisher Scientific, Fair Lawn, NJ, USA) with a conductivity in the range of 20 to 25 mS/cm.

Two sets of ED ion exchange membrane stacks (i.e., ED-EX and ED-ME) were manufactured by SnowPure, LLC (San Clemente, CA, USA) and Mega AS (Stráž pod Ralskem, Czech Republic), respectively, and their properties are presented in Table S2 (Supporting Information, available online at <http://www.iwaponline.com/wst/068/533.pdf>). These two sets of ED membrane stacks were used to dialyze OSPW and BDW samples, and these membrane stacks are commonly tested in the lab-scale ED systems (EET-Corporation 2011). Each ED membrane stack consisted of alternating AEM and CEM placed between the two

electrodes. Each membrane stack was composed of 20 pairs of AEM and CEM; the total effective surface area of the membrane stacks was 0.1422 m². The schematic diagram of the ED system is shown in Figure S1 (Supporting Information, available online at <http://www.iwaponline.com/wst/068/533.pdf>). The treatment efficiency was evaluated with respect to (i) two different voltages (20 V and 70 V), (ii) four different concentrate/diluate volume ratios (1:1, 1:2, 1:5, and 1:10) and (iii) with and without diluate stream reuse in the concentrate stream. The acceptable voltage range of the ED system is 20–80 V (EET-Corporation 2011); therefore, 20 and 70 V were selected as low and high voltage applications to avoid permanent damage of the membrane. In this study, the different volume ratios were tested to determine the optimum ratio of concentrate to diluate stream which would minimize the operational and maintenance costs. The treated diluate stream was used as a concentrate stream for evaluating water reuse for the ED treatment process.

Water characterization

An Accumet XL60 pH/conductivity meter (Fisher Scientific Inc., Fair Lawn, NJ, USA) was used to measure pH and conductivity of the samples. The COD, TDS and total suspended solids (TSS) concentrations in OSPW and BDW matrices were determined by following the *Standard Methods for the Examination of Water and Wastewater* (Greenberg & Eaton 1998). Turbidity of water samples was measured using a digital nephelometric turbidimeter (Orbeco-Hellige Inc., Sarasota, FL, USA). The total organic carbon (TOC) concentration was measured by an Apollo 9000 TOC combustion analyzer (FOLIO Instruments Inc., Kitchener, ON, Canada). Each sample was analyzed in triplicate. The AEF was measured by Fourier transform infrared spectroscopy method using extraction process (Pourrezaei *et al.* 2011). The total alkalinity as calcium carbonate (CaCO₃) was determined by titration with 0.02 N sulfuric acid (H₂SO₄). Ion chromatography (ICS-2000 and ICS-2500, Dionex, Sunnyvale, CA, USA) was employed to analyze cations and anions in OSPW and BDW samples before and after ED treatment. One-way analysis of variance was used to validate the data differences. The results were reported as *p*-values; *p*-values of less than 0.05 suggested that the differences were statistically significant.

Cost analysis

A cost analysis was undertaken to estimate the capital expenditures (CapEx) as well as operational and maintenance

expenditures (OpEx) associated with high pressure-driven (e.g., reverse osmosis (RO)) (Kim *et al.* 2011) and electricity-driven (e.g., ED) membrane deionization plants capable of desalinating 4.0 million cubic meters of oil sands water per year. Equipment cost data for RO and ED treatment facilities were obtained from the technical reports of the companies that sell membranes (Filteau & Moss 1997). The equipment comprises a chemical injection skid, an RO or ED system, acid and caustic pumps, acid and base tanks, a neutralisation tank, a system controller, and a blower. CapEx consisted of direct and indirect costs (Green & Perry 2008). Direct costs included equipment purchase, delivery, installation, instrumentation and control, piping, electrical, buildings, yard improvement and site work, and a service facility. Indirect costs included taxes, permits, indirect materials, procurement, construction management, installation supervision, commissioning, allowances for temporary facilities, insurance, and large cranes. OpEx were calculated from the general maintenance, chemicals, materials, energy, labor, disposal, and trucking costs. Cited cost data were recalculated using inflation rates for the year 2012 (Parsons *et al.* 2012), the Chemical Engineering's Plant Cost Index (CEPCI) (CEPCI 2012), and the seven-tenths rule (Green & Perry 2008).

Fort McMurray, Alberta, located 450 km northeast of Edmonton, is a major hub of the oil sands industry in Canada. Because it is located far from a city business centre (i.e., Edmonton), prices for labor, delivery, housing, disposal, and trucking were estimated two to three times higher in Fort McMurray than the prices for a conventional site in an urban location. Labor costs may vary depending on the project, time frame, and competitive contract negotiations. Land price was not included in the cost analysis because these plants are likely to be built on an oil sands company's property. Project calculation parameters and assumptions are listed in Table S3 (available online at <http://www.iwaponline.com/wst/068/533.pdf>). All costs are given in Canadian dollars (C\$).

RESULTS AND DISCUSSION

CFS pretreatment and treatment performance of the ED system

Jar-tests for CFS pretreatment of OSPW and BDW were performed. The conductivity and turbidity of OSPW and BDW before and after CFS pretreatment are shown in Table S4 (available online at <http://www.iwaponline.com/wst/068/533.pdf>). The turbidity of both waters decreased after CFS

pretreatment due to formation of flocs and their subsequent settling during the sedimentation process. As opposite, conductivities of waters were only slightly reduced after the CFS pretreatment.

For ED treatment, all samples were pretreated with the CFS process, and both EX series (membrane stack ED-EX) and ME series (membrane stack ED-ME) were used to deionize OSPW and BDW. Experiments were conducted at a room temperature (22 ± 1.0 °C) and 20 V of the applied voltage. The removal efficiencies of various water constituents by different membrane stacks in OSPW and BDW are listed below in Table 1.

The treatment efficiency of OSPW and BDW during ED resulted in very high ion-removal efficiency of all measured parameters; however, the removal efficiencies observed with ED-EX were slightly higher with respect to several

components (e.g., ammonium, sulfate and bromide in BDW) comparing to ED-ME. No turbidity and TSS were detected after CFS and ED treatment with either membrane stack in both OSPW and BDW. The conductivity of OSPW was decreased by 98.9 and 98.4% after ED-EX and ED-ME treatments, respectively. The same types of treatments decreased the conductivity of BDW in the diluate stream by 99.2 and 99.1%, respectively. The removal efficiency of AEF compounds was also quite high in both waters. During OSPW treatment, the removal efficiencies of AEF were 96.9 and 96.5% by ED-EX and ED-ME, respectively. Removal efficiencies of 88.4 and 89.8% for ED-EX and ED-ME, respectively, were recorded during the treatment of BDW. In OSPW, averages of 99.3% of all ions (i.e., cationic and anionic species) were removed through the ED-EX and ED-ME treatments. The average removal efficiencies of ionic species in BDW were 96.6% for ED-EX and 93.4% for ED-ME. The total alkalinity was also reduced by more than 98.0% in both OSPW and BDW at any applied treatment. By comparing the removal efficiencies of individual compounds, it can be seen that the performance of ED-EX stack was slightly better.

Table 1 | Removal efficiencies of components in OSPW and BDW treated with CFS and ED processes

Species	Removal efficiency, %			
	OSPW ED-EX	ED-ME	BDW ED-EX	ED-ME
Turbidity ^a , NTU	100.0	100.0	100.0	100.0
Total suspended solids ^a , mg/L	100.0	99.9	100.0	100.0
Total organic carbon ^a , mg/L	96.3	95.1	79.3	76.7
Conductivity, $\mu\text{S}/\text{cm}$	98.9	98.4	99.2	99.1
Chemical oxygen demand, mg/L	98.6	98.8	97.9	97.3
Total dissolved solids, mg/L	98.7	98.3	99.4	99.4
Acid extractable fraction, mg/L	96.9	96.5	88.4	89.8
Calcium, mg/L	99.7	99.8	98.6	97.3
Magnesium, mg/L	100.0	100.0	97.9	97.3
Sodium, mg/L	98.6	98.1	99.5	99.4
Potassium, mg/L	100.0	100.0	95.7	96.3
Ammonium, mg/L	100.0	100.0	89.1	79.6
Sulfate, mg/L	99.0	98.9	96.0	94.8
Chloride, mg/L	97.9	97.6	99.3	99.3
Fluoride, mg/L	100.0	100.0	100.0	100.0
Nitrate, mg/L	99.8	99.5	100.0	100.0
Nitrite, mg/L	100.0	100.0	n/a ^b	n/a ^b
Bromide, mg/L	100.0	100.0	90.4	68.1
Phosphate, mg/L	n/a ^b	n/a ^b	97.1	95.3
Carbonate, mg/L	99.4	99.4	99.8	99.7
Bicarbonate, mg/L	99.2	98.6	99.5	99.4
Total alkalinity, mg/L	99.2	98.6	99.5	99.3

^aTurbidity, total suspended solids and total organic carbon are mostly removed by CFS pretreatment process.

^bNot applicable. The concentration of original source water was zero.

Effects of applied voltage

Reductions in conductivity of OSPW and BDW were investigated at 20 and 70 V at a room temperature with a 1:1 volume ratio of concentrate to diluate. Deionized water (DI) was used as a concentrate stream source. The ion exchange membranes in ED-EX stack were employed to deionize OSPW and BDW with a conductivity of 50 $\mu\text{S}/\text{cm}$ in the diluate stream as the manufacturer suggested. Figure 1 shows conductivity changes in electrode, concentrate, and diluate streams in terms of operating time and applied voltage.

ED treatment of OSPW and BDW at 20 V caused a decrease in diluate (feed water) conductivities (Figures 1(a) and (c); closed squares). At 20 V, the conductivity of OSPW diluate decreased from 4,280 to 40 $\mu\text{S}/\text{cm}$ after 6 h of operation (Figure 1(a)) and the conductivity of BDW diluate decreased from 23,930 to 50 $\mu\text{S}/\text{cm}$ after 8 h of operation (Figure 1(c)). When the applied voltage was increased to 70 V, OSPW and BDW diluate conductivities decreased from 3,970 and 23,320 $\mu\text{S}/\text{cm}$, respectively, to below 50 $\mu\text{S}/\text{cm}$ after 4 h of treatment. The ion migration rate was proportional to the electrical potential across the membrane stack (Perez *et al.* 1994) and the deionization rate increased with the increase in the applied voltage.

The conductivity of the concentrate stream increased with operating time due to ion transport from the diluate

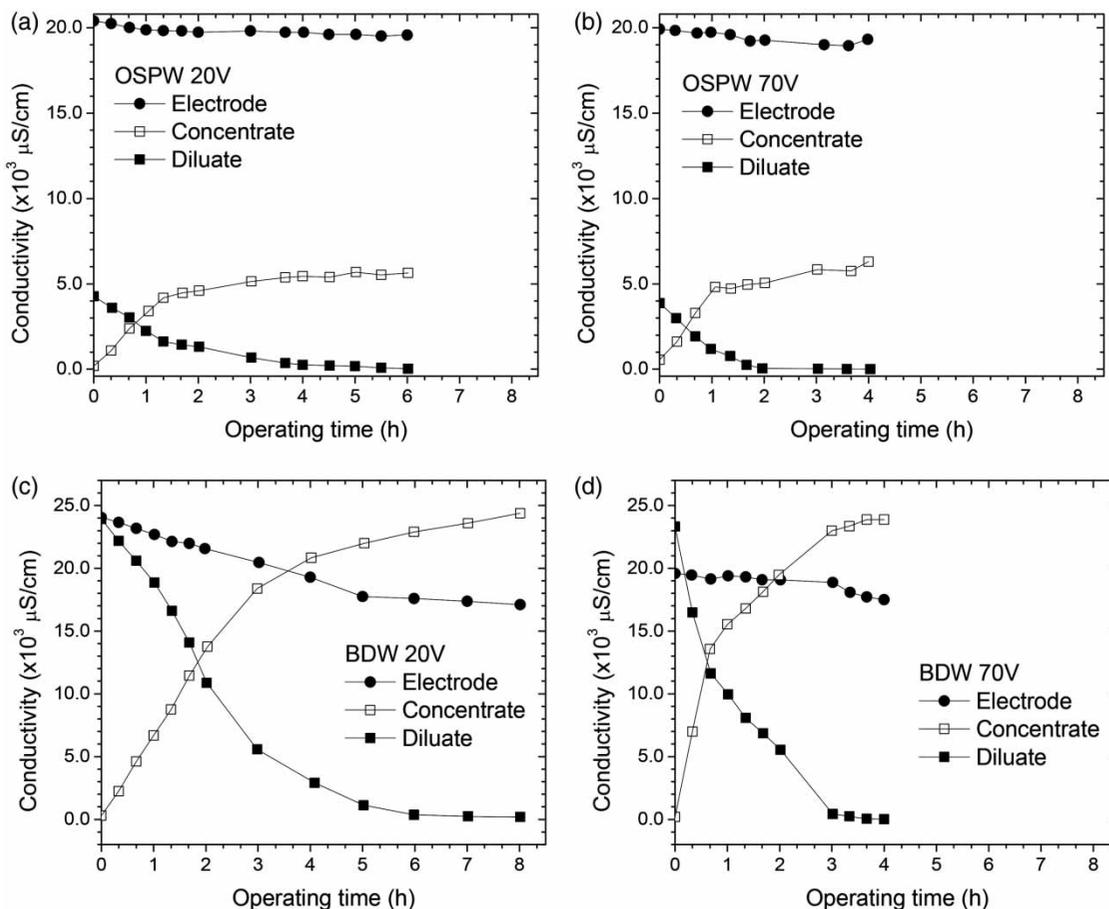


Figure 1 | Conductivities of electrode, diluate, and concentrate streams as a function of the operating time at different applied voltages: (a) OSPW at 20 V; (b) OSPW at 70 V; (c) BDW at 20 V; and (d) BDW at 70 V.

stream. Conductivity variance in the electrode stream measured over treatment time was statistically insignificant during ED treatment of OSPW ($p > 0.05$); however, there was a slight drop in the electrode stream conductivity during BDW treatment, especially at the applied voltage of 20 V ($p = 0.037$) (Figure 1(c)). The conductivity of both OSPW and BDW diluate streams decreased quickly in the initial 2–3 h of ED treatment. After 3 h, the decrease in the conductivity was less compared to the initial treatment time, indicating saturation of the ion exchange capacity of the membranes (Li & Zou 2011). The operating time was shorter for OSPW than for BDW due to higher initial conductivity of BDW.

Effect of stream volume ratio

The concentrate to diluate stream volume ratio is an important factor in deionization by ED treatment because it represents the volume of the concentrate stream that will need to be disposed after water has been treated. Different

volume ratios of concentrate to diluate streams were tested with the ED-EX membrane stack using CFS-pretreated OSPW or BDW as the diluate stream, DI water as the source of the concentrate stream, and at the applied voltage of 20 V. Conductivity changes in the diluate stream are shown in Figure 2.

OSPW diluates with the initial conductivities of $4,461 \mu\text{S/cm}$ and 1:10 concentrate:diluate volume ratios decreased to $47 \mu\text{S/cm}$ after being dialysed for 12 h; OSPW diluates with the same initial conductivity and 1:5 concentrate:diluate ratios were reduced to $49 \mu\text{S/cm}$ after 9 h of ED treatment. BDW diluates with the initial conductivities of $22,870 \mu\text{S/cm}$ and concentrate:diluate volume ratios of 1:10 decreased to $49 \mu\text{S/cm}$ after being dialysed for 10.3 h; BDW diluates with the same initial conductivity and 1:5 concentrate:diluate volume ratios decreased to $50 \mu\text{S/cm}$ after 8 h of ED treatment. Similar results for other concentrate to diluate volume ratios were observed in both OSPW and BDW. Operation time increased with the decrease in concentrate to diluate volume ratio; initial

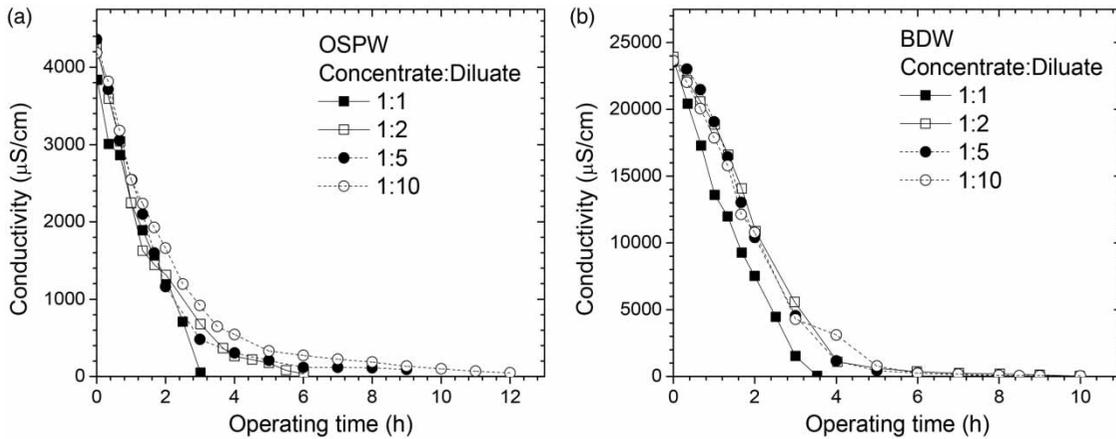


Figure 2 | Conductivity of diluate stream (a) OSPW or (b) BDW versus operation time for different concentrate to diluate stream volume ratios.

ion concentration (i.e., conductivity) did not affect ion removal efficiency.

Effect of treated diluate stream for recycle

To save the cost of producing DI water and to evaluate if a continuous flowing ED system would be practical, CFS-pretreated OSPW or BDW were used as a diluate stream, and treated diluate was used as a concentrate stream. The volume ratio of concentrate to diluate streams was 1:5 and the applied voltage was 20 V. As is shown in **Figure 3**, conductivity was decreased within 8 h of ED operating time in both OSPW and BDW. The conductivity of treated water (reused OSPW: 49.4 $\mu\text{S}/\text{cm}$ and DI 48.1 $\mu\text{S}/\text{cm}$, and reused BDW: 49.2 $\mu\text{S}/\text{cm}$ and DI 47.9 $\mu\text{S}/\text{cm}$) was not statistically significant ($p > 0.05$). Both DI water and reused diluate showed similar trends in the reduction of conductivity in the diluate, and the diluates could therefore be

used as concentrate streams in an ED system. This means that an ED system could be operated without the addition of DI water. This would save the cost of DI water and permit the design of a continuous ED system.

Cost analyses

The results of the cost analyses are listed in **Table 2**. RO and ED costs were calculated to be \$4.43 and \$4.48, respectively, per cubic meter for the conventional urban condition, and \$10.62 and \$10.71, respectively, per cubic meter for the Fort McMurray condition.

The analyses in **Table 2** are relevant to the factors that have a large impact on the CapEx and OpEx. ED treatments entailed energy consumption three times higher than that of RO treatments. Labor costs in Fort McMurray were estimated to be three times higher than those at a conventional site because of the higher benefits, allowances, insurance,

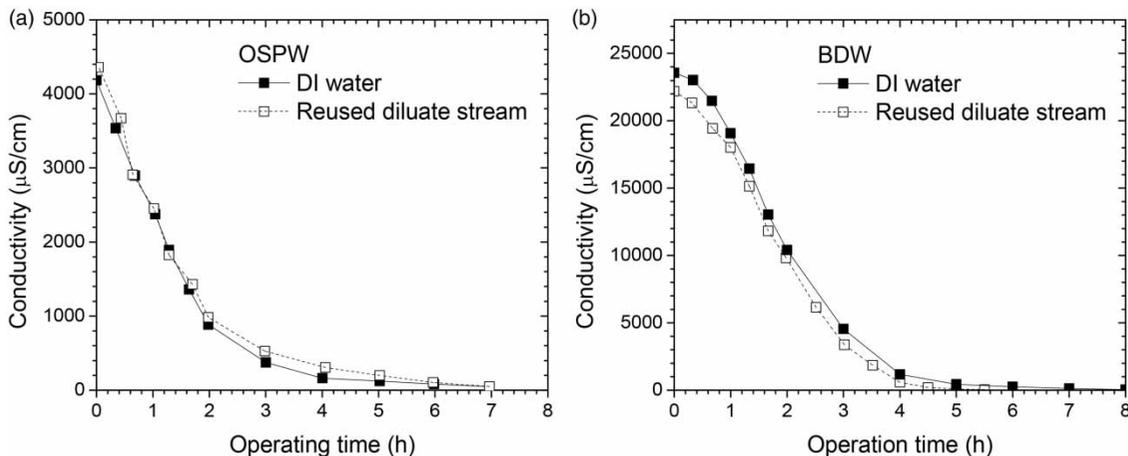


Figure 3 | Comparison of concentrate streams of DI water and treated diluate with a conductivity below 50 $\mu\text{S}/\text{cm}$ in the ED deionization of (a) OSPW and (b) BDW.

Table 2 | CapEx and OpEx analyses for RO and ED treatment plants in conventional and Fort McMurray conditions

	Conventional urban condition		Fort McMurray condition	
	RO	ED	RO	ED
Estimated CapEx ^a , \$/yr	\$974,522	\$892,973	\$4,506,529	\$4,129,417
Estimated OpEx ^b , \$/yr	\$16,756,009	\$16,832,004	\$37,968,028	\$38,196,012
Energy	\$181,440	\$596,160	\$544,320	\$1,788,480
Labor	\$735,337	\$735,337	\$2,206,010	\$2,206,010
Chemicals	\$291,282	\$200,000	\$873,845	\$600,000
Materials	\$70,687	\$5,709	\$212,062	\$17,128
Other (maintenance, disposal)	\$15,477,264	\$15,470,798	\$34,131,792	\$34,112,395
Total annual expenses, \$/yr	\$17,730,531	\$17,900,977	\$42,474,557	\$42,853,430
Estimated cost per volume of processed water, \$/m ³	\$4.43	\$4.48	\$10.62	\$10.71

^aCapEx: capital expenditures.

^bOpEx: operational and maintenance expenditures.

and pensions commanded by workers at a rural worksite. Chemical costs of RO were calculated to be higher than ED due to more fouling of the high-pressure membranes compared to ion exchange membranes. RO and ED costs to treat oil sands processed water are high due to a short membrane lifespan and trucking costs for the disposal. Membrane replacement is a significant cost concern in the oil sands industry because the average membrane life is decreased due to membrane fouling caused by high turbidity of the oil sands waters (Kim *et al.* 2011). Trucking costs for the processed water disposal were assumed to be \$250 per hour and truck haul capacity was assumed to be 25 tonnes. The waste management site in Alberta is more than 450 km away from Fort McMurray, leading to higher disposal and trucking costs. It should be noted that the main purpose of this cost analysis was to compare the relative costs of water treatment technologies. As such, the analysis does not represent an accurate cost for each treatment technology.

A breakdown of average costs for operating a desalination plant in Fort McMurray is shown in Figure S2 (available online at <http://www.iwaponline.com/wst/068/533.pdf>). CapEx for RO and ED water treatments was estimated to be 10.6 and 9.6% of the total expenses per year, respectively, i.e. \$4.5 and \$4.1 M/yr, in the Fort McMurray condition. Equipment costs for RO were slightly higher than for ED because the high-pressure-driven membrane system is more costly than the ion exchange system (Gerard & Laflamme 2008). Disposal and trucking costs are expected to be predominant in OpEx, with over 80% of the total expenses per year. Material amounts for trucking and disposal and labor costs were assumed to be similar for RO and ED. Maintenance costs of RO and ED are

expected to be similar (0.5% of the total expenses per year), and material and chemical costs of RO were considered to be higher than those of ED due to the shorter lifespan of polymeric membrane and the need to use a variety of chemicals for antifouling and cleaning. Image captures of the cost evaluation sheets for RO and ED treatments are attached in Tables S5–S8 (available online at <http://www.iwaponline.com/wst/068/533.pdf>).

CONCLUSIONS

One of the greatest environmental risk management challenges facing the Alberta oil sands industry today is the desalination of oil sands processed waters that result from bitumen mining. This study evaluated the efficiencies of ED technology in the treatments of OSPW and BDW, and resulted in high removal efficiencies of all measured components. ED yielded a constant quality product with minimal control and the standard empirical parameters (i.e., applied voltage and stream volume ratio). The results of this study presented the possibility of a continuous ED operation that reuses the diluate stream as a source for the concentrate stream. Automation of such a continuous ED treatment system would decrease the costs of DI water intake, operational costs, and energy costs. ED efficiency with respect to water residence time, durability of membrane stacks and electrodes, diluate quality, and volume of concentrate should be considered in a full-scale operation. The approximate cost of producing water of acceptable quality for recycling was \$10.71/m³ for ED compared to \$10.62/m³ for RO.

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SUPPLEMENTARY MATERIAL

The supporting information (available online at <http://www.iwaponline.com/wst/068/533.pdf>) provides additional tables (including Microsoft Excel® spreadsheet) and figures.

REFERENCES

- Allen, E. W. 2008a *Process water treatment in Canada's oil sands industry: I. Target pollutants and treatment objectives*. *Journal of Environmental Engineering and Science* **7** (2), 123–138.
- Allen, E. W. 2008b *Process water treatment in Canada's oil sands industry: II. A review of emerging technologies*. *Journal of Environmental Engineering and Science* **7** (5), 499–524.
- CEPCI 2012 Chemical Engineering's Plant Cost Index. <http://www.che.com/pci/>.
- EET-Corporation 2011 *Installation, Operation and Maintenance Manual, HEED Model Laboratory Scale System*. EET Corporation, Harriman, TN, USA.
- Filteau, G. & Moss, P. 1997 *Ultra-low pressure RO membranes: an analysis of performance and cost*. *Desalination* **113** (2–3), 147–152.
- Gamal El-Din, M., Fu, H., Wang, N., Chelme-Ayala, P., Pérez-Estrada, L., Drzewicz, P., Martin, J. W., Zubot, W. & Smith, D. W. 2011 *Naphthenic acids speciation and removal during petroleum-coke adsorption and ozonation of oil sands process-affected water*. *Science of The Total Environment* **409** (23), 5119–5125.
- Gerard, R. & Laflamme, R. 2008 *Technology Selection Tools for Boiler Feedwater Applications*. GE Water & Process Technologies, Technologies GWP, Trevose, PA, USA.
- Green, D. W. & Perry, R. H. 2008 *Perry's Chemical Engineers' Handbook*, 8th edn, McGraw-Hill, New York.
- Greenberg, A. E. & Eaton, A. D. 1998 *Standard Methods for the Examination of Water and Wastewater*. American Public Health Association/American Water Works Association/Water Environment Federation, Washington, DC.
- Hwang, G., Dong, T., Islam, M. S., Sheng, Z., Pérez-Estrada, L. A., Liu, Y. & Gamal El-Din, M. 2013 *The impacts of ozonation on oil sands process-affected water biodegradability and biofilm formation characteristics in bioreactors*. *Bioresource Technology* **130**, 269–277.
- Kim, E.-S., Liu, Y. & Gamal El-Din, M. 2011 *The effects of pretreatment on nanofiltration and reverse osmosis membrane filtration for desalination of oil sands process-affected water*. *Separation and Purification Technology* **81** (3), 418–428.
- Kim, E.-S., Liu, Y. & Gamal El-Din, M. 2012 *Evaluation of membrane fouling for in-line filtration of oil sands process-affected water: the effects of pretreatment conditions*. *Environmental Science & Technology* **46** (5), 2877–2884.
- Li, H. & Zou, L. 2011 *Ion-exchange membrane capacitive deionization: a new strategy for brackish water desalination*. *Desalination* **275** (1–3), 62–66.
- Martin, J. W., Barri, T., Han, X., Fedorak, P. M., El-Din, M. G., Perez, L., Scott, A. C. & Jiang, J. T. 2010 *Ozonation of oil sands process-affected water accelerates microbial bioremediation*. *Environmental Science and Technology* **44** (21), 8350–8356.
- NEB 2006 *Canada's Oil Sands, Opportunities and Challenges to 2015: an Update*. National Energy Board, Calgary, AB, Canada.
- Parsons, M., Gainer, A. & Shama, S. 2012 *Alberta Economic Trends, Economics, Demography and Public Finance*. Government of Alberta Finance, Edmonton, AB, Canada.
- Perez, A., Andres, L. J., Álvarez, R., Coca, J. & Hill, C. G. 1994 *Electrodialysis of whey permeates and retentates obtained by ultrafiltration*. *Journal of Food Process Engineering* **17** (2), 177–190.
- Pourrezaei, P., Drzewicz, P., Wang, Y., Gamal El-Din, M., Perez-Estrada, L. A., Martin, J. W., Anderson, J., Wiseman, S., Liber, K. & Giesy, J. P. 2011 *The impact of metallic coagulants on the removal of organic compounds from oil sands process-affected water*. *Environmental Science & Technology* **45** (19), 8452–8459.
- Van der Bruggen, B., Koninckx, A. & Vandecasteele, C. 2004 *Separation of monovalent and divalent ions from aqueous solution by electrodialysis and nanofiltration*. *Water Research* **38** (5), 1347–1353.
- Van Geluwe, S., Braeken, L., Robberecht, T., Jans, M., Creemers, C. & Van der Bruggen, B. 2011 *Evaluation of electrodialysis for scaling prevention of nanofiltration membranes at high water recoveries*. *Resources, Conservation and Recycling* **56** (1), 34–42.