Desalination and Water Treatment 2 (2009) 278–286
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Electrodialysis reversal: Process and cost approximations for treating coal-bed methane waters

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Received 4 March 2008; Accepted 28 December 2008

ABSTRACT

Brackish waters with total dissolved solids (TDS) concentrations less than 10,000 mg/L are extracted from coal-beds in the Wyoming Powder River basin to facilitate the production of coal-bed methane. These waters frequently require treatment before disposal or use. Electrodialysis reversal (EDR) has not yet been used to treat these waters but this technology should be suitable. The question is whether EDR would be cost-effective. The purpose of this work, then, was to develop models for predicting the cost of EDR for brackish waters. These models, developed from data available in the literature, were found to predict actual EDR costs as a function of TDS removal, influent flow rate, chemical rejection efficiency, water recovery, electricity use, and labor cost within 10% of reported values. The total amortized cost for removing 1,000 mg/L of TDS from 10,000 m^3/day of influent assuming no concentrate disposal costs was predicted to range from \$0.23/m^3 to \$0.85/m^3 and was highly dependent on capital cost and facility life. Concentrate disposal costs significantly affected total treatment cost, providing a total treatment cost range from \$0.38/m^3 to \$6.38/m^3, depending on concentrate disposal cost and water recovery. Pilot demonstrations of EDR in the Powder River basin should be conducted to determine the achievable water recovery when treating these waters.

Keywords: Electrodialysis; Electrodialysis reversal; Costs; Desalination; Coal-bed methane water; Water treatment

1. Introduction

Coal-bed methane (CBM) production is an important industry in many jurisdictions including: Colorado, Wyoming, Appalachia, Texas, Alabama, Louisiana, and Montana [1]. One important CBM production area is the Powder River basin (PRB) of northeastern Wyoming. In this area alone, 13,600 wells have produced 1.35 trillion cubic feet (TCF) of methane from 1987 through May 2004 [2]. The remaining CBM to be recovered is estimated at 25.2 TCF in the PRB [3], which is approximately 18 times the amount that has already been recovered.

CBM in the PRB of Wyoming is produced by dewatering the coal-beds thus allowing the methane to desorb from the coal and be released for recovery. Typically, 0.34 m^3 of water must be removed, on average, to produce 1 ft^3 of CBM [2]. In the arid climate of north-eastern Wyoming, CBM-produced water should be an important resource. The quality of these waters, however, varies across the PRB. In the eastern Cheyenne River watershed, water quality is high [2] and CBM-produced waters can be used to irrigate croplands or can be directly discharged to receiving waters. CBM-produced waters from other watersheds may contain constituents such as sodium at sufficiently high levels to preclude their use without treatment.

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Across the PRB, CBM-produced waters have sodium concentrations between 110 and 800 mg/L and total dissolved solids concentrations between 270 and 2010 mg/L [2,4–8]. These waters also have low calcium and magnesium concentrations ranging from 5.9 to 69 mg/L and 2 to 46 mg/L, respectively [4], leading to sodium adsorption ratio (SAR) values ranging from 5.7 [4] to 33 [2]. Waters with high SAR values are not suitable for irrigation because the excess sodium displaces calcium and magnesium in the soils causing damage to the soil structure [9]. Permitted ranges for discharge of CBM-produced waters in the PRB are 270–350 mg/L, 10–24, and 310–5000 mg/L, for sodium, SAR, and TDS, respectively [10]. While other constituents in CBM-produced waters are also regulated, such as barium, iron, chloride, sulfate, and arsenic [10], the primary challenge with these waters is to decrease the sodium concentration.

Cation exchange is currently widely used in the PRB to remove sodium because the concentrations of calcium and magnesium are low compared to sodium and bicarbonate is the primary anion with concentrations of 290–2320 mg/L [4]. Bicarbonate is currently not regulated and sulfate, at concentrations of 0–17 mg/L [4], has so far been below discharge limits.

Electrodialysis reversal (EDR) is capable of removing cations and anions from brackish waters (TDS ≤10,000 mg/L). Although EDR has been widely used elsewhere [11], it has not yet been used for CBM-produced waters in the PRB, perhaps because of limited cost data. The cost-effectiveness of EDR cannot be appropriately compared to other technologies such as cation exchange without cost information. Such comparisons may become important if the water quality criteria become more stringent with respect to anion concentrations and cation exchange becomes technically infeasible.

The objective of this paper, then, is to predict the costs of using EDR to treat brackish waters, including those with characteristics similar to CBM-produced waters in the PRB. Specifically, the cost predictions should be a function of influent water constituent concentrations, influent water flow rate, effluent water constituent requirements and other key factors such as concentrate disposal cost and electricity cost. To facilitate these predictions, a mathematical model was constructed that incorporates technical and economic data and the results were compared to actual treatment costs.

2. Technical performance of EDR

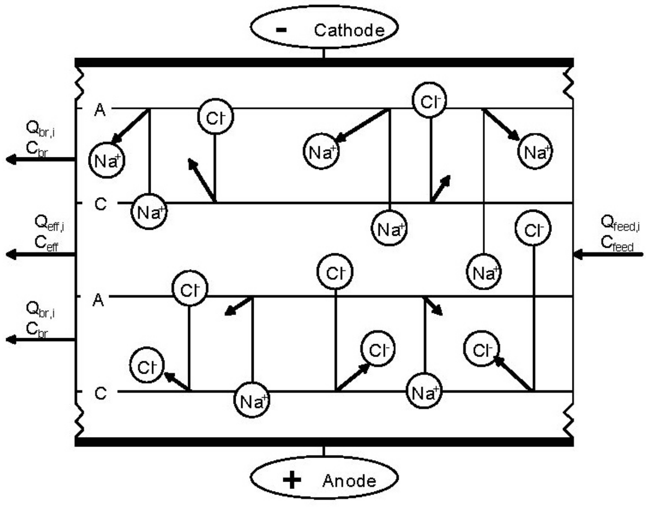
2.1. Description of the technology

Electrodialysis is an electrochemical separation process in which ions move through charged, semi-permeable, ion-selective membranes due to an electrical potential difference. The ion selective membranes allow only anions or cations to cross them and can be made even more selective by decreasing the pore size so that only monovalent ions are removed from solution [12].

An applied electrical potential between the positively charged anode and negatively charged cathode (Fig. 1) induces an electrical current through the solution. This causes cations to migrate toward the cathode (negative electrode) and anions to migrate toward the anode (positive electrode). Cations (illustrated as Na^+ in Fig. 1) pass through the cation selective membrane (C), and anions (illustrated as Cl^- in Fig. 1) pass through the anion selective membrane (A). Because cations cannot migrate through an anion selective membrane and vice versa, a concentrate stream that contains both ions is produced (illustrated as a sodium chloride solution in Fig. 1). Back diffusion of ions through the membrane is limited by the potential difference and the resulting current.

Electrodialysis is typically performed in a stack (or module) with the membranes oriented vertically and separated by flow spacers. Water flows between the membranes and then passes through additional stacks in series if further ion removal is required. Membrane stacks operated in parallel are typically referred to as a stage.

EDR follows the same principles as electrodialysis but with the polarity of the stack reversed periodically to remove solids that may form on the membranes during normal operation. When using EDR instead of electrodialysis, chemical pretreatment to consume alkalinity is



Symbol	Definition
Na^+	Sodium
Cl^-	Chloride
A	Anion Selective Membrane
C	Cation Selective Membrane
i	One flow channel

Fig. 1. Schematic of the electrodialysis process.

not required because precipitates that may form on the membranes are removed during polarity reversal. This results in decreased chemical costs [12].

Technology specific parameters such as chemical rejection efficiency determine the number of stages required to reduce the ion concentrations to the discharge regulation. Lower chemical rejection efficiency per stack means higher capital costs because more stacks are required. Water recovery also impacts operating costs because water that enters the concentrate channel must be further managed. Increased concentrate volumes will increase the concentrate management costs.

2.2. Chemical rejection efficiency

The chemical rejection, or ion removal, efficiency describes the performance of an EDR system and depends on the membrane type, the feed TDS of the water, and the electrical potential across the stack. The effluent ion concentration for an EDR system can be determined from the chemical rejection efficiency as indicated in Eq. (1).

$$C_{eff,i} = (\mathrm{CRE})^N \cdot C_{feed,i} \tag{1}$$

where $C_{eff,i}$ is the effluent concentration (mg/L) of constituent i, CRE is the chemical rejection efficiency per stage, N is the number of stages required to achieve the desired effluent concentration, and $C_{feed,i}$ is the feed constituent concentration (mg/L). The constituent requiring the largest number of stages to achieve effluent criteria is the limiting constituent.

Schoeman and Thompson [12] determined that chemical rejection efficiencies for EDR facilities range between 40% and 60% per stage. Also, Hays [13] reported 50% TDS removal per stage. So assuming a 50% chemical rejection efficiency per stage and a feed TDS concentration equal to 1,000 mg/L, Eq. (1) predicts the TDS concentration for each stage of a three-stage system as 500 mg/L for stage 1, 250 mg/L for stage 2 and 125 mg/L for stage 3.

2.3. Water recovery

A water balance around an EDR system [Eq. (2)] shows the three key flows: Q_{feed}, the feed flow rate (m^3/d); Q_{eff}, the effluent flow rate (m^3/d); and Q_{conc}, the concentrate flow rate (m^3/d).

$$Q_{feed} = Q_{eff} + Q_{conc} \tag{2}$$

The water recovery, η_r, is then defined by Eq. (3):

$$\eta_r = 100\frac{Q_{eff}}{Q_{feed}} \tag{3}$$

Theoretically, water losses in an EDR system are attributed only to the water associated with ions (which form an ionic hydraulic radius) as ions migrate through the membrane [12]. Therefore, the transport of water through the membrane and the water recovery can be related to the TDS removal of an EDR system as described by Eq. (4) [12]:

$$\eta_\mathrm{r} = 100 - \left(5\times10^{-4}\right)\cdot\left(C_{feed,TDS} - C_{eff,TDS}\right) \tag{4}$$

where $C_{feed,TDS}$ is the feed TDS concentration (mg/L) and $C_{eff,TDS}$ is the effluent water TDS concentration (mg/L).

The theoretical water recovery [Eq. (4)] does not compare well with data collected by Leitner and Associates [14] (Fig. 2). The averages and standard deviations for the Leitner and Associates [14] data are 79% ± 8% for water recovery and 895 ± 660mg/L for TDS removal. In practice, water may be added to the concentrate flow channels to reduce fouling potential and scale formation, thus decreasing recovery [12]. Recent developments in membrane technology now allow EDR systems to operate at constituent concentrate concentrations well above saturation. For example, Turek et al. [15] achieved 93.1% water recovery when operating an EDR at 364% calcium sulfate saturation.

3. Cost characteristics of EDR

3.1. Capital costs

EDR treatment costs depend on technology specific parameters (chemical rejection efficiency, water recovery, electrical use, labor requirements and parts replacement), economic parameters (electrical cost, labor rate, and concentrate disposal cost), and treatment requirements (TDS removal and influent flow rate). The key factors that affect the capital cost of an EDR system are the required TDS removal and system capacity [12,16]. Capital costs for EDR systems were not available from vendors due to the proprietary nature of such costs. Therefore, capital costs were collected from the literature and adjusted to 2007 dollars using appropriate construction cost indices (CCI) [17,18]. This method accounts for inflation and is outlined in Eq. (5).

$$CC_{2007} = CC_{xxxx} \times \frac{CCI_{2007}}{CCI_{xxxx}} \tag{5}$$

where CC_{2007} is the capital cost adjusted to 2007 ($US), CC_{xxxx} is the capital cost in the reported year ($US), CCI_{2007} is the construction cost index for the year 2007 (unitless), CCI_{xxxx} is the construction cost index for the reported year (unitless). The CCI_{xxxx} values used are summarized in

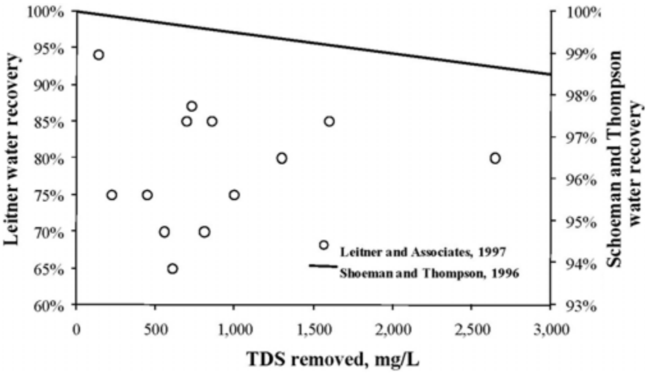


Fig. 2. Theoretical and actual water recoveries as a function of influent TDS.

Table 1
Construction cost indices used to adjust literature capital costs to 2007 dollars [17,18]

Year built	Cost index
1975	2212
1977	2576
1979	3003
1984	4146
1989	4615
1990	4732
1991	4835
1993	5210
1995	5471
1998	5920
2007	7879.6

Table 1. Eq. (5) was also used to adjust literature operating cost estimates to 2007 ($US).

Urano [19] surveyed EDR capital costs in Japan for systems achieving 85% water recovery. A range of flow rates (Q_{feed}) was examined, from 100 to almost 10,000 m^3/d for systems removing 1,000, 3,000 and 10,000 mg/L of TDS. The 2007 capital costs ranged from $920,000 to $22.9 million. Larson and Leitner [20] surveyed EDR capital costs in the US. The flow rates ranged from 3,785 to 37,854 m^3/d and two TDS removals were examined (1,300 and 3,148 mg/L). The 2007 capital costs ranged from $3.4 million to $36.7 million. Leitner and Associates [14] collected capital cost data for a range of systems in the US constructed between 1975 and 1995. The flow rates ranged from 379 to 17,034 m^3/d and TDS removals ranged from 143 to 3,400 mg/L. The 2007 capital costs ranged from $1.3 million to $11.5 million. Lawrence et al. [16] received estimates from an EDR vendor for a 636 m^3/d system for treating CBM waters in Lysite, Wyoming. The 2007 capital costs were $1.4 million, $1.85 million and $2.1 million for TDS removals of 5,000, 7,500 and 9,000 mg/L, respectively.

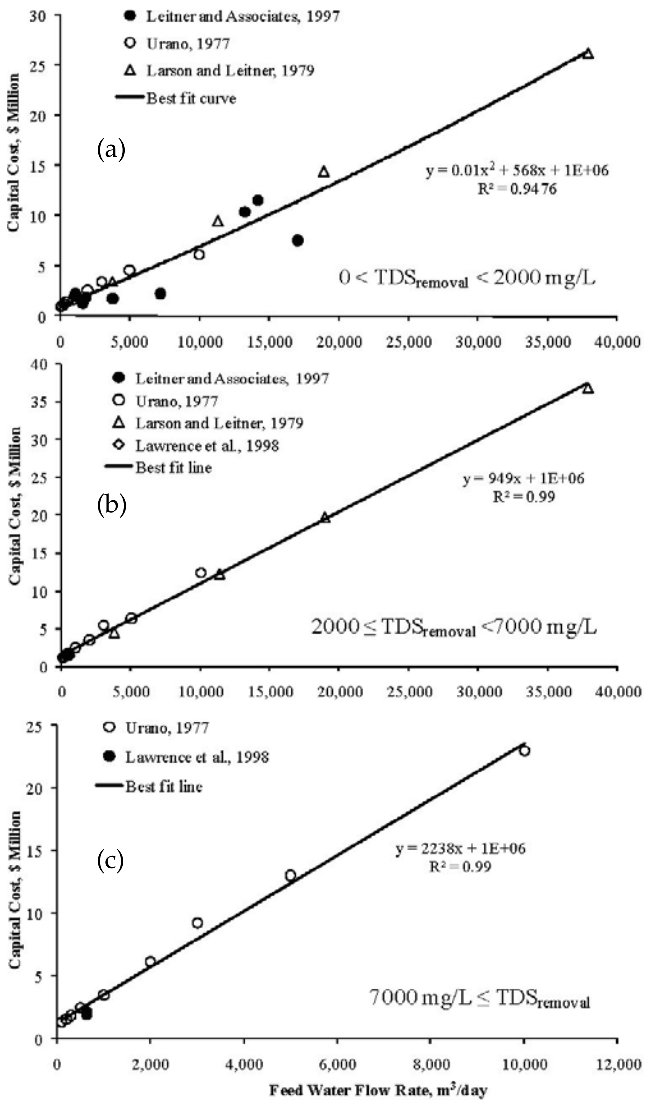


Fig. 3. EDR capital costs. (a) 0 <$\text{TDS}_{\text{removal}}$ <2000 mg/L; (b) 2000 ≤$\text{TDS}_{\text{removal}}$ <7000 mg/L; (c) 7000 mg/L ≤$\text{TDS}_{\text{removal}}$.

To determine expressions for estimating capital costs as a function of system capacity (feed water flow rate), the 2007 capital costs were segregated by TDS removal into three groups. Capital costs for systems removing less than 2,000 mg/L TDS are shown in Fig. 3a, systems removing between 2,000 and 7,000 mg/L TDS are shown in Fig. 3b and systems that removed 7,000 mg/L TDS or more are shown in Fig. 3c. Least-squares regression conducted in Microsoft Excel was used to determine the best fit line or curve for each data set. The function for each regression is shown in Eqs. (6)–(8) where CC_{EDR} is the capital cost (2007 dollars) as a function of Q_{feed} (m^3/d) for Q_{feed} ≥100 m^3/d. The y-intercept of the separate regressions was approximately $1 million and so the regressions were redone, holding the y-intercept equal to $1 million. This approximates the fixed capital costs for a system treating 100 m^3/d and removing 2,000 mg/L TDS or less. Smaller EDR systems (Q_{feed} <100 m^3/d) may be available for less than $1,000,000, but no data were found to support this.

$$CC_{EDR} = 0.01 \cdot Q_{feed}^2 + 568 \cdot Q_{feed} + 1{,}000{,}000 \quad (r^2 = 0.95)$$
$$\text{for } 0 < \text{TDS}_{\text{removal}} < 2000 \text{ mg/L} \tag{6}$$

$$CC_{EDR} = 949 \cdot Q_{feed} + 1{,}000{,}000 \quad (r^2 = 0.99) \tag{7}$$
$$\text{for } 2000 \leq \text{TDS}_{\text{removal}} < 7000 \text{ mg/L}$$

$$CC_{EDR} = 2238 \cdot Q_{feed} + 1{,}000{,}000 \quad (r^2 = 0.99) \tag{8}$$
$$\text{for } 7000 \text{ mg/L} \leq \text{TDS}_{\text{removal}}$$

3.2. Operating costs

Operating costs for EDR were estimated as the sum of the costs for electricity, labor, chemicals, membrane replacement, and miscellaneous parts replacement [Eq. (9)]:

$$OC_{\text{EDR}} = OC_{\text{elec}} + OC_{\text{labor}} + OC_{\text{chem}} + OC_{\text{mem}} + OC_{\text{parts}} \tag{9}$$

where OC_{EDR} is the total unit operating cost ($\$/m^3$), OC_{elec} is the unit electricity cost ($\$/m^3$), OC_{labor} is the unit labor cost ($\$/m^3$), OC_{chem} is the unit chemical cost ($\$/m^3$), OC_{mem} is the unit membrane replacement cost ($\$/m^3$), and OC_{parts} is the unit miscellaneous parts replacement cost ($\$/m^3$).

Electrical usage depends on the desired TDS removal, hydraulic pressure drop from stage to stage [12], concentrate recirculation rate, pumping equipment efficiency, and feed water temperature [21]. Data from Leitner and Associates [14] and Lawrence et al. [16] relating electrical usage to TDS removal are shown in Fig. 4. There is tremendous variability in the data, with unit electrical usage ($\text{Elec}_{\text{usage}}$) ranging from less than 0.25 kWh/m^3 at 2,700 mg/L TDS removal to over 4 kWh/m^3 for 3,200 mg/L TDS. The linear, least-squares regression of the data [Eq. (10)] provides only a general relationship between TDS removal and electricity usage. The unit electricity cost is then determined from Eq. (11):

$$Elec_{\text{usage}} = 6\times10^{-4}\,(C_{\text{feed,TDS}} - C_{\text{eff,TDS}}) + 0.1153$$
$$(r^2 = 0.64) \tag{10}$$

$$OC_{\text{elec}} = Elec_{\text{usage}}\,(Price_{\text{elec}}) \tag{11}$$

where $Price_{\text{elec}}$ is the electricity price ($/kWh).

The labor requirement for an EDR system was assumed to be 1 full-time employee per 1,229 m^3/d of water treated [14]. The cost for one employee ($Cost_{\text{employee}}$) was assumed to be $50,000/y; therefore the unit cost of labor (OC_{labor}) is $\$0.1115/m^3$.

Chemical usage associated with an EDR system is typically attributed to periodic cleaning of the membrane surfaces with dilute acids [12]. The actual cost of chemicals at the Suffolk, Virginia, EDR facility was $\$0.0052/m^3$ in 1998 [22] or $\$0.007/m^3$ in 2007 dollars. This value is used as the unit chemical cost (OC_{chem}) for EDR.

Membrane replacement is required every 12 to 15 years for properly operated EDR systems [23]. Schoeman and Thompson [12] and the US Bureau of Reclamation [21] suggested that approximately 10% of the membranes must be replaced annually providing a more conservative ten year membrane life. Assuming a 10-year membrane life, planners predicted the unit membrane replacement cost at the Suffolk, Virginia, EDR facility to be $\$0.0159/m^3$ [12] or $\$0.0220/m^3$ in 2007 dollars.

Miscellaneous parts replacement costs also impact the total treatment cost for EDR. Leitner and Associates [14] collected annual miscellaneous parts replacement and chemical cost data for different size EDR facilities. The average parts and chemical cost ($OC_{\text{parts}} + OC_{\text{chem}}$) from the Leitner and Associates [14] was $\$0.013 \pm 0.008/m^3$. Subtracting OC_{chem} ($\$0.007/m^3$) provides OC_{parts} equal to $\$0.006/m^3$. Werner and von Gottberg [22] found the parts replacement cost at the Suffolk, VA, facility to be $\$0.055/m^3$ ($\$0.073/m^3$ adjusted to 2007 US $) which included membrane, electrode and miscellaneous parts replacement. Subtracting membrane replacement cost and averaging both sets of data provide an approximate miscellaneous parts replacement cost of $\$0.0285/m^3$.

Pretreatment may also be required to remove particulate matter (<0.5 tubidity units), iron (<0.3 mg/L), manganese (<0.1 mg/L), sulfide (<0.1 mg/L) and scale-forming substances (silica, calcium sulfate, and barium sulfate) from the feed water [21]. The impact of these cost components has been neglected because most PRB CBM co-produced waters are below the recommended maximum feed water concentrations [2,4–8], and therefore do not require extensive pretreatment.

3.3. Total costs for EDR

Concentrate disposal represents a potentially important cost for EDR, especially in areas like the PRB in Wyoming where there are no suitable bodies of salt water to accept concentrate. The concentrate disposal cost (CDC_{EDR}, $\$/m^3$ of influent water) can be determined from Eq. (12) where CDC_u is the concentrate disposal cost per m^3 of concentrate.

$$CDC_{EDR} = CDC_u \cdot \frac{Q_{\text{conc}}}{Q_{\text{feed}}} \tag{12}$$

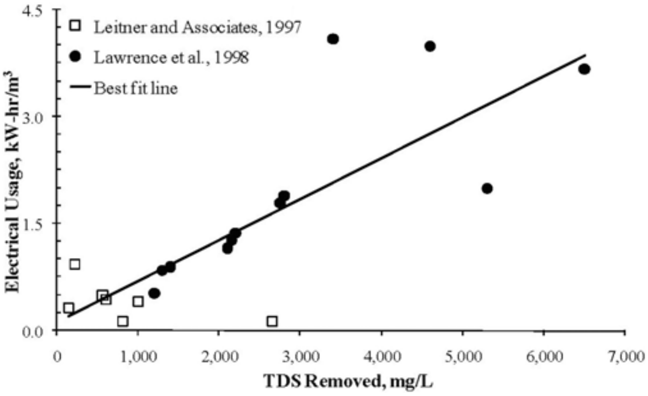


Fig. 4. EDR electrical usage with respect to TDS removal.

The total treatment cost for an EDR system (TC_{EDR}) can now be approximated with Eq. (13) where ACC_{EDR} is determined by Eq. (14) and represents the amortized unit capital cost (\$/m^3), assuming straight depreciation and a service life equal to L_s (years).

$$TC_{\mathrm{EDR}} = ACC_{\mathrm{EDR}} + OC_{\mathrm{EDR}} + CDC_{\mathrm{EDR}} \tag{13}$$

$$ACC_{EDR} = \frac{CC_{EDR}}{365 L_s Q_{feed}} \tag{14}$$

4. Results and discussion

4.1. Validation

The validity of the developed equations for predicting EDR costs were tested using data from Hays [13]. These data were not used to develop the equations. Hays [13] reported actual EDR treatment costs for a water treatment plant in Washington, Iowa. The design capacity for this system was 4,164 m^3/d (1.1 mgd) and TDS removal was 527 mg/L. This system was designed for 85% water recovery and the concentrate disposal cost was assumed to be \$0/m^3.

The total capital cost reported by Hays [13] was \$1,800,000 (1991 dollars) or \$2,933,460 (2007 dollars). The capital cost estimated from Eq. (6) was \$3,399,829, only 14% higher than the adjusted capital cost reported by Hays [13].

Hays [13] also determined the total EDR cost assuming 6% interest and a 20-y life. This cost included the operating and maintenance costs discussed above and also included components that are unnecessary for treating PRB CBM waters including: deep well pumping, high service pumping, and filters. After subtracting the operating costs that are not relevant for PRB CBM water, assuming no interest and adjusting to 2007 dollars, the total treatment cost from Hays [13] was \$0.287/m^3. The equations developed above predict the total EDR cost to treat this water under the same conditions and neglecting interest to be \$0.314/m^3, less than 10% greater than that reported by Hays [13]. This validation suggests that the cost prediction equations developed herein are suitable for budget level estimates.

Table 2
EDR cost modeling assumptions and results for an influent flow rate and TDS removal of 10,000 m^3/d and 1,000 mg/L, respectively

Parameter	Base	High	Low
Capital, \$	6,800,000[a]	8,600,000	5,160,000
Life, y	10	15	5
Electricity, kW-h/m^3	0.715[b]	1.43	0.358
Labor, \$/m^3	0.1115	0.223	0.056

[a] Determined from Eq. (6).
[b] Determined from Eq. (10).

4.2. Sensitivity

A sensitivity analysis was conducted to determine the relative impacts of capital cost, facility life, electricity use and labor cost on the total cost of an EDR system. This was done by examining a system designed to remove 1,000 mg/L of TDS (a typical level required for PRB CBM water treatment) from an influent flow of 10,000 m^3/d. The four key inputs were assigned base, high and low values as indicated in Table 2. High and low values are base plus and minus 25% for capital, base plus or minus 50% for facility life and double or half of base for electricity usage and labor, respectively. The price of electricity was assumed constant at \$0.07/kWh, the cost of chemicals was assumed constant at \$0.007/m^3, membrane replacement costs were assumed constant at \$0.022/m^3 and miscellaneous parts were assumed constant at \$0.0285/m^3. Concentrate disposal cost was neglected in this analysis (considered separately in Section 4.3 below).

The sensitivity analysis results are summarized in Table 3. When electricity and labor are held constant at the base levels from Table 2, the total treatment costs range from a low of \$0.31/m^3 for the low capital cost and 15 yr facility life to a high of \$0.69/m^3 for the high capital cost and 5 yr facility life. Not surprisingly, treatment costs decrease with an increased facility life because straight line depreciation has been assumed, but this trend also indicates that an EDR facility should be built to last as long as possible to reduce overall treatment costs. Total treatment costs are highly sensitive to amortized capital costs. The impact from a 25% difference in capital cost is about \$0.10/m^3.

Table 3
Sensitivity analysis results (units are \$/m^3 of influent water and assumptions are outlined in Table 2)

Facility life, y		5			10			15		
Capital cost		Base	High	Low	Base	High	Low	Base	High	Low
Electricity and labor	Base	0.60	0.69	0.50	0.41	0.45	0.36	0.34	0.38	0.31
	High[a]	0.76	0.85	0.66	0.57	0.62	0.52	0.51	0.54	0.47
	Low[b]	0.52	0.61	0.42	0.33	0.37	0.28	0.26	0.30	0.23
Electricity[c]	High	0.65	0.74	0.55	0.46	0.50	0.41	0.39	0.43	0.36
	Low	0.57	0.67	0.48	0.38	0.43	0.34	0.32	0.35	0.29
Labor[d]	High	0.71	0.80	0.61	0.52	0.57	0.47	0.46	0.49	0.42
	Low	0.54	0.63	0.45	0.35	0.40	0.30	0.29	0.32	0.26

[a] Electric and labor are both at High level from Table 2.
[b] Electric and labor are both at Low level from Table 2.
[c] Labor is constant at Base level from Table 2.
[d] Electric is constant at Base level from Table 2.

Table 4
Sensitivity analysis results as percent (%) contribution of each cost to total treatment cost (assumptions are outlined in Table 2)

Facility life, yrs		5			10			15		
Capital cost		Base	High	Low	Base	High	Low	Base	High	Low
Electricity[a]	Base	8	7	10	12	11	14	15	13	16
	High	15	14	18	22	20	24	25	23	28
	Low	4	4	5	7	6	7	8	7	9
Labor[b]	Base	19	16	22	27	25	31	32	30	36
	High	32	28	36	43	39	47	49	46	52
	Low	10	9	13	16	14	18	19	17	22
Capital[c]	Base	63	68	56	46	52	39	36	42	30

[a] Labor is constant at Base level from Table 2.
[b] Electricity is constant at Base level from Table 2.
[c] Electricity and labor are both constant at Base level from Table 2.

The sensitivity of total treatment cost to electricity usage is particularly important, given the variability in the data used to produce Eq. (10). Doubling the base electrical usage predicted from Eq. (10) resulted in a \$0.05/m^3 increase in total treatment cost on average while halving resulted in a \$0.025/m^3 decrease in total treatment cost. This range of electrical usage approximates the largest variations from Eq. (10) shown in Fig. 4 for TDS removal of 1,000 mg/L. As Table 3 shows, the total cost is relatively insensitive to electricity usage, with the four-fold difference between the high and low electricity usage estimates providing total cost estimates within 25%.

Total treatment cost was also sensitive to labor costs. A doubling of labor costs resulted in a \$0.11/m^3 increase in total treatment cost on average while halved labor costs resulted in a \$0.05/m^3 decrease in overall treatment cost. Of the different conditions summarized in Table 3, the highest estimated treatment cost was \$0.85/m^3 for the high capital, high electric and high labor scenario with a 5 year facility. The lowest estimated cost of \$0.23/m^3 was predicted for the low capital, low electric and low labor scenario with a 15-year life.

The total treatment cost was sensitive to all four variables examined, as indicated in Table 3. To determine the most important variable for a given scenario, the percent contribution of each variable to the total cost was determined (Table 4). The contribution of capital costs to total cost when electricity and labor were held constant at their base levels varied from 30% for the low level capital cost and 15 year facility life scenario to 68% for the high level capital costs and 5-year facility life scenario. The contribution of capital to the total treatment cost was greater than the contribution of the other variables for all scenarios except high level labor costs with a 15-year facility life and high level labor costs with a low level capital cost and 10-year facility life. Labor costs were the largest contributor in those cases. The contribution of labor costs ranged from 9% to 52% of the total treatment cost and the contribution of electricity usage costs ranged from 4% to 28%. The results shown in Table 4 must be

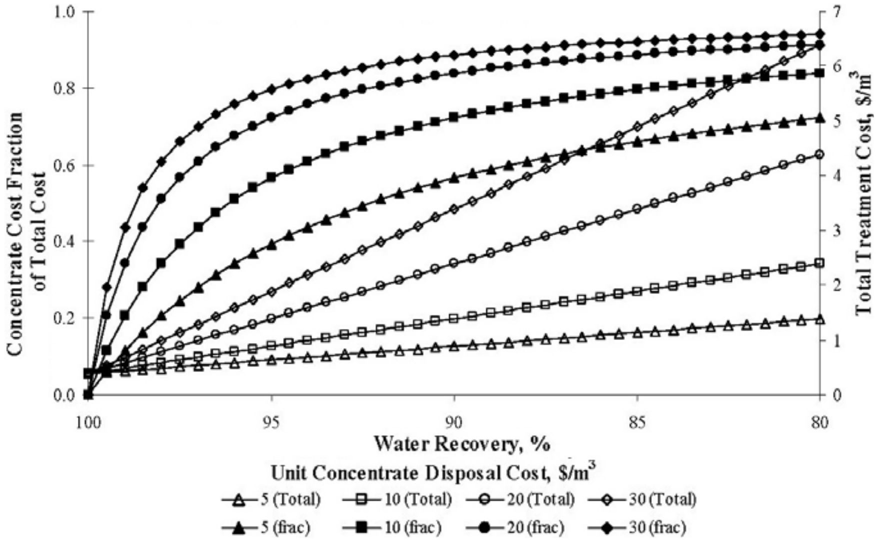


Fig. 5. Concentrate cost fraction and total treatment cost as a function of water recovery and unit concentrate disposal costs for a system treating 10,000 m^3/d and removing 1,000 mg/L TDS.

considered in conjunction with those in Table 3, however. The high sensitivity of the total treatment cost to capital cost means that for any given scenario, the total cost decreases significantly as the facility life increases, at least between facility lives of 5–15 years.

4.3. Water recovery and concentrate disposal

If concentrate disposal is free, then water recovery has little impact on the total cost of the treatment system and water recovery can be estimated from either Eq. (4) or assumed to be an average value from Fig. 2 (for example). In the PRB, however, concentrate disposal is not free. This is expected to be the case for many inland desalination facilities. Concentrate disposal costs in the PRB may range from less than \$5/m^3 of concentrate [24] to \$30/m^3 of concentrate [25] depending on the concentrate management technique employed. The quantity of concentrate to be disposed is a direct function of water recovery [Eqs. (2) and (3)] so to minimize cost, water recovery should be optimized. To evaluate the impact of these potentially important factors, water recovery and concentrate disposal costs were varied for a system treating 10,000 m^3/d of water and removing 1,000 mg/L of TDS. The other parameters were held constant at their base levels (Table 2) and as mentioned in Section 4.2.

The total treatment cost is significantly affected by decreasing water recovery and increasing concentrate disposal costs (Fig. 5). At concentrate disposal costs of \$1/m^3 concentrate or less, the impact of decreasing water recovery from 99.5% [predicted by Eq. (4)] to 80% (average recovery in Fig. 2) is a relatively moderate increase of \$0.18/m^3 in total treatment cost, from \$0.38/m^3 to \$0.56/m^3. The fraction of the total cost due to concentrate disposal, however, increases from 0.01 to 0.34.

The impact of concentrate disposal cost and water recovery on the total treatment cost becomes much more pronounced as concentrate disposal cost increases. For example, if the concentrate disposal cost is \$30/m^3 and water recovery is 99.5%, the total treatment cost is \$0.54/m^3 (Fig. 5) and the fraction of the total cost attributed to concentrate disposal is 0.28 (Fig. 5). If the water recovery cannot be optimized, however, and is only 80%, the total treatment cost increases by a factor of 11.8 to \$6.39/m^3 and the fraction of the total cost attributed to concentrate disposal increases to 0.94. Concentrate disposal costs are clearly non-trivial and will be an important factor in determining the cost-effectiveness of any inland desalination technology.

5. Conclusions

The equations developed to estimate EDR treatment costs for treating brackish waters similar to coal-bed methane co-produced waters in the Wyoming Powder River Basin are suitable for providing budget level estimates. These predictions could be used for preliminary comparisons between EDR and other desalination technologies that might be used for these waters. While capital cost, facility life, labor cost and electricity usage each significantly impact the total treatment cost of an EDR system, the combined effects of capital cost and facility life provide the largest contribution. This may significantly disadvantage EDR vs. other technologies for treatment situations where a treatment facility life of less than 10 years is required. On the other hand, if capital costs can be reduced, EDR may be a highly cost-effective technology.

Water recovery and concentrate disposal costs are critical components for estimating total treatment cost (the combination of concentrate disposal cost and water recovery provided a range of total treatment costs from \$0.38/m^3 to \$6.38/m^3). These issues will be similar for any technology treating brackish waters in an inland environment. The possible potential of EDR to operate at very high water recoveries, especially for the relatively low TDS removals required in the Powder River Basin may decrease concentrate volumes sufficiently vs. other desalination technologies to help offset the high capital cost of the technology. Pilot and demonstration testing of EDR with PRB CBM waters is needed to further refine the operating window with respect to water recovery and concentrate production.

Acknowledgements

The United States Department of Energy has funded this research under National Energy Technology Laboratory Award No. DE-FC26-06NT15568.

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