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Probabilistic cost estimation methods for treatment of water extracted during CO_2 storage and EOR

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ABSTRACT

Extraction and treatment of in situ water can minimize risk for large-scale CO_2 injection in saline aquifers during carbon capture, utilization, and storage (CCUS), and for enhanced oil recovery (EOR). Additionally, treatment and reuse of oil and gas produced waters for hydraulic fracturing will conserve scarce fresh-water resources. Each treatment step, including transportation and waste disposal, generates economic and engineering challenges and risks; these steps should be factored into a comprehensive assessment. We expand the water treatment model (WTM) coupled within the sequestration system model CO_2-PENS and use chemistry data from seawater and proposed injection sites in Wyoming, to demonstrate the relative importance of different water types on costs, including little-studied effects of organic pretreatment and transportation. We compare the WTM with an engineering water treatment model, utilizing energy costs and transportation costs. Specific energy costs for treatment of Madison Formation brackish and saline base cases and for seawater compared closely between the two models, with moderate differences for scenarios incorporating energy recovery. Transportation costs corresponded for all but low flow scenarios (<5000 m^3/d). Some processes that have high costs (e.g., truck transportation) do not contribute the most variance to overall costs. Other factors, including feed-water temperature and water storage costs, are more significant contributors to variance. These results imply that the WTM can provide good estimates of treatment and related process costs (AACEI equivalent level 5, concept screening, or level 4, study or feasibility), and the complex relationships between processes when extracted waters are evaluated for use during CCUS and EOR site development.

1. Introduction

Extraction of in situ water (referred to here as "extracted water") is a critical option for minimizing the impacts and enhancing large-scale CO_2 injection in saline aquifers during carbon capture, utilization, and storage (CCUS). The potential reuse of extracted ("produced") waters derived from oil and gas production processes is also a key issue during enhanced oil recovery (EOR) and hydraulic fracturing for shale gas and oil. For sequestration, water may be extracted from storage reservoirs during CO_2 injection in order to control the movement of CO_2 in the subsurface, to control system pressures, and to increase available pore space. Commercial-scale CCUS may require large volumes of water to be extracted, on the order of cubic kilometers over 30 years (Middleton et al., 2012). For the oil and gas industry, reuse of produced water creates a constant, drought-proof source of water for drilling and completions. Treatment and use of these extracted waters could provide alternative resources to replace fresh-water demands for carbon capture processes, thermoelectric cooling, hydraulic fracturing, and other water uses for carbon-capture power plants and industrial use. However, extracted waters typically have complex chemistries, including a wide range of total dissolved solids (TDS) (up to 200,000 mg/L or greater); high organic carbon contents (μg/L to percent range); and high concentrations of scale-forming minerals (e.g., carbonates, sulfates) (Klapperich et al., 2012). The waters at times may also contain naturally-occurring radioactive materials (NORM, as Ra-226 and Ra-228) (Attallah et al., 2013; Fakhru'l-Razi et al., 2009). Disposal of the waste products from desalination can be costly, particularly when deep well injection is required for the concentrated effluent ("concentrate") (Mickley, 2006). While site-specific engineering analysis clearly can define the costs to treat a specific water source (Kobos et al., 2011), little analysis has been conducted to understand the broader significance and impacts of cumulative process choices, or varying source properties, on the

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overall cost trends of treatment for CO_2 storage-extracted waters (hereafter, “extracted waters”). Each step of treatment, including treated product transportation and waste concentrate disposal, generates additional economic and engineering challenges and risks; these need to be factored into a comprehensive assessment in order to fully understand and evaluate water treatment options. When viewed as a whole system, nearly every process choice is linked to one or more process outcomes. Knowledge of these costs with respect to other system costs for carbon capture, utilization, and storage (CCUS) can help evaluate the economic impacts associated with CCUS system design and implementation. Evaluating treatment process selections, the costs of these processes, and the tradeoffs of the costs and processes are an important portion of overall system understanding, risk assessment, and total cost of the CCUS system.

Variations in temperature, pressure, and salinity are primary factors that affect water treatment choices (Sullivan et al., 2013). State-of-the-art reverse osmosis (RO) treatment for marine-type water chemistries (TDS ~35,000–40,000 mg/L) is well understood and readily assessed for costs and process choices (Fritzmann et al., 2007; Campos, 2013). However, marine-type chemistry conditions are not common among extracted waters (Klapperich et al., 2012; Sullivan et al., 2013; Greenlee et al., 2009; Bourcier et al., 2011). Higher salinities (>45,000 mg/L TDS) in extracted waters will require thermal methods (e.g., multi-stage flash [MSF] or multiple-effect distillation [MED]); we have shown these methods to be more cost effective than membrane treatments in some circumstances (Sullivan et al., 2013). The International Energy Agency Greenhouse Gas (IEAGHG) program presented treatment cost analyses for four specific locations worldwide; variance in costs was related to water extraction rate but not to transportation; variable salinity was considered, but not other aspects of geochemistry (Klapperich et al., 2012). Others have examined treatment of extracted water within the inorganic geochemical constraints of carbon storage on aquifer geochemistry (Bourcier et al., 2011; Wolery et al., 2009; Buscheck et al., 2011). Beneficial use of coal-bed methane waters, including geochemistry and treatment, was examined by Dahm et al. (2011). Among these studies, there is a need for better analysis of treatment scenarios as a part of a total system approach to understanding the effects of process choices on overall costs and risks to CCUS scenarios (Middleton et al., 2012).

The cost of electricity, pretreatments (organic and inorganic), and transportation strongly impact the total cost of treatment (Campos, 2013). While total energy (thermal and electric combined) use for thermal desalination processes is higher than other processes (40–120 kWh/m^3), electricity is typically the sole power source for membrane treatments such as RO (3.5–4.5 kWh/m^3) or nanofiltration (NF) (Campos, 2013). Electricity use is strongly correlated with total RO costs, because electricity is used to drive the pumps that create pressure on the separation membranes (IAEA, 2011; Desalination, 2008; Georgopoulou et al., 2001). The higher the system salinity, the more electrical energy consumed, up to the point where membranes are no longer effective (>~45,000 mg/L TDS) because of membrane osmotic potential limitations (Fritzmann et al., 2007; Georgopoulou et al., 2001). Energy recovery from the pressurized system on the concentrate side of the membrane is now routinely performed by using devices such as Pelton turbines or turbochargers, and has been very effective at driving down the overall costs of membrane treatments (Pankratz, 2005).

Inorganic pretreatments to remove divalent constituents (Ca^{2+}, Mg^{2+}, $SO_4{}^{2-}$, Ba^{2+}) and other constituents (Fe, silica) are used to prevent scaling and fouling in both membrane systems and thermal treatment systems, although thermal treatments by design use pretreatments less frequently (Ebrahim et al., 1995). Pretreatment includes acid and/or antiscalent chemical additions to prevent mineral scale formation, aeration, and micro- or ultrafiltration to remove particulates. Water types requiring pretreatment based on their affinity for fouling are discussed by El-Manharawy and Hafez (2003); many of the waters extracted for carbon storage purposes are expected to have not only high chloride concentrations (>100 mMol/kg Cl^- or >10,000 mg/L TDS by EPA regulation) (EPA, 2014), but will also have high sulfate fouling potential based upon SO_4/Alkalinity ratios (>10; seawater ~10) and high carbonate fouling potentials (typically found in waters between 4000 mg/L and ~45,000 mg/L TDS) (Klapperich et al., 2012; Bourcier et al., 2011; Aines et al., 2011; Millero et al., 1998). A similar situation exists for oil and gas produced waters (Collins, 1975; Tibbetts, 1992). Even though guidelines are available to develop pretreatment methods and costs for seawater RO (e.g., Dow, 2013), little information is available regarding costs, and therefore sensitivity, for pretreatment of extracted or produced waters.

There are currently no models for treatment of extracted water that adequately address organic pretreatment (Klapperich et al., 2012; IAEA, 2011). The use of EOR reservoirs for carbon storage means a likelihood that extracted water will contain organic constituents from oil residues. These constituents may cause fouling of membrane or thermal systems, may be toxic, and liable for regulation (Shaffer et al., 2013). Membrane manufacturers suggest that the organic content in feed waters be reduced to <0.5 mg/L to prevent fouling (Dow, 2013). Consequently, organic pretreatment is necessary prior to RO and NF membrane treatment, and often is advisable for thermal treatments to prevent air emissions of toxic, volatile chemicals. Engineering design models for membrane desalination plants usually rely on seawater composition which includes moderate, known ranges of polar organic compounds such as organic acids (Greenlee et al., 2009; Dow, 2013; Das et al., 2008; Coşkun et al., 2012); for waste-water treatment, known composition and concentration data is preferred. For extracted waters, information is scarce; in particular, the National Carbon Sequestration Database and Geographic Information System (“NATCARB”) does not yet contain significant dissolved or total organic content information for sequestration formations (NETL, 2012). To fill this data gap, we can use characterization information in the literature for oil and gas produced waters and EOR waters that contain from <1 μg/L to >11,000 mg/L concentrations of total organic carbon (TOC) (Neff and Stout, 2002). TOC in EOR reservoir waters includes not only organic acids, but nonpolar, volatile and semivolatile, aliphatic, and aromatic organic compounds. Different types of organic compounds require different types of pretreatment. There are many different options for treatment of organic constituents in water, with widely varying capabilities and costs (Kruithof et al., 2007; Hickey et al, 1994; Ranck et al., 2005). Free-phase oils or colloids are often removed by oil-water separation or dissolved air flotation (DAF). Dissolved non-polar organic compounds can be removed by sorption, oxidation, air stripping or vapor extraction, and biological degradation methods. Dissolved polar compounds are removed via oxidation, membrane separation (e.g., nanofiltration), biological degradation, ion exchange, or precipitation. A lack of specific composition and concentration information, and, thus, poorly defined pretreatment choices, may lead to poor estimations of costs for organic pretreatment of extracted waters. The variance in these costs should be considered as a part of the total cost profile of the system.

Transportation costs are more easily quantifiable than pretreatments, can contribute to costs at multiple steps in the treatment process, and have interdependencies with other treatment aspects including concentrate disposal and delivery of treated water to the end user. For example, Class II well disposal is a common method for disposal of saline oil and gas produced water, and may be an important option for disposal of EOR concentrate from extracted waters. However, if this option is not available locally (e.g., as in the

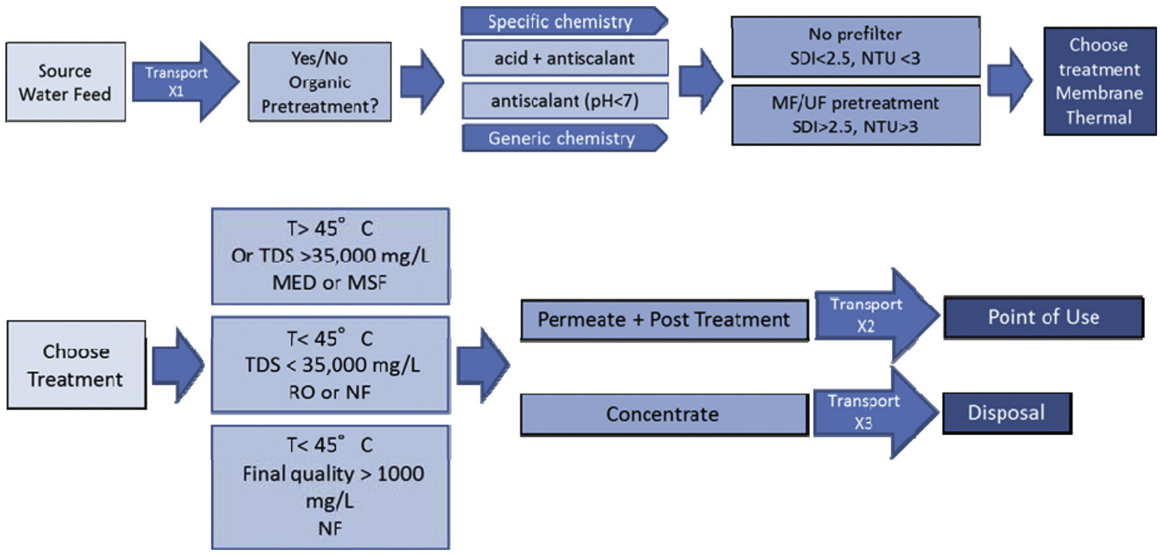

Fig. 1. Schematic of water treatment module. Top: Pretreatment phases. Bottom: Treatment and post-treatment phases. Transportation segments are designated as X1, X2, and X3. Pretreatments are defined as generic (source water chemistry unknown, generic cost applied), or specific (chemistry known and input by user, specific costs applied).

Marcellus region of Pennsylvania), then transportation to the disposal point becomes increasingly significant as a cost contributor to the disposal portion of the treatment train.

System models that include both primary (treatment train) and secondary or peripheral processes (transport to and from treatment; regulatory constraints) can expand our knowledge of the costs, risks, and impacts on the feasibility of large-scale treatment of extracted waters. The WTM uses more complexity than informal calculations, and incorporates up-to-date cost and process information, but is not intended to be a rigorous engineering design model. The cost estimation is equivalent to DOE/AACEI cost estimation level 5 (concept screening) or level 4 (study or feasibility) (AACEI, 2011). Stochastic data sets, such as water quality, feed water temperature, and volumes, are incorporated easily into the model. User input such as site location, and distance to a disposal or treated water point-of-use are included. This type of model captures the major contributors to costs, without needing detailed site data, and while allowing sensitivity analysis and importance analysis for multiple variables to improve decision making. Here we describe use of the CO_2-PENS water treatment module (WTM) to assess potential CO_2 storage-extracted waters for costs of some primary and secondary processes that are significant to risk analysis and decision making. We examine the importance of transportation by truck and pipeline, the importance of pretreatment methods (for inorganic and organic foulants), the relationships of these costs with disposal choices, and show a relative performance comparison of the WTM with an engineering-based treatment design model (Klapperich et al., 2012; IAEA, 2011).

2. Methods

2.1. CO_2-PENS water treatment module

The WTM was developed using the GoldSim© platform (Sullivan et al., 2013; GoldSim, 2014). GoldSim© is used to develop analysis models that perform multi-realization, probabilistic simulations. A FORTRAN code captures the logic of treatment process selection and is linked within GoldSim©. GoldSim uses custom data elements for input of user-specified parameters including stochastic distributions. The WTM captures all decision points; both stochastic range and constant data input values. Fig. 1 shows a model schematic diagram including user-specified and model-calculated

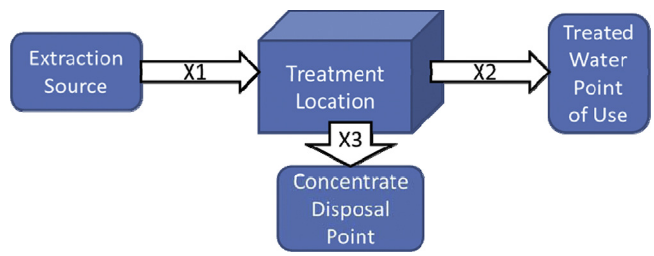

Fig. 2. Simple transportation model.

factors. For this study, we have expanded WTM capability to address pretreatments for organic foulants, TDS composition effects on inorganic pretreatment choices (acid, antiscalent, or both), and a bimodal transportation model (truck and pipeline) (Fig. 2). The WTM includes the effects of regulation on multiple disposal choices and the effects of location (regional climate) and water type (produced or not produced) on disposal choices (e.g., Class I, Class II, or Class V wells) (Sullivan et al., 2013). Treatment choices are selected based on influent water volume, temperature, and composition. The WTM includes two modes for pretreatment costing: a generic pretreatment cost mode based on literature-reported treatment costs (Sullivan et al., 2013), that is activated based upon the user-reported pH of the water and adds a generic quantity of acid and/or antiscalent; and a specific scaling-potential calculation mode that accounts for scale-forming ion concentrations in the influent, that adds a calculated amount of acid and antiscalent based on specific user-reported mineral element concentrations in the water (Dow, 2013). We refer to these modes as either "generic" or "specific" throughout the text. For CO_2 storage applications, costs are calculated in terms of US dollars/ton of CO_2 stored; for water treatment applications costs are calculated in terms of US dollars/m^3 of water treated. Table 1 lists ranges of input parameters (design basis) for potential extracted and produced water types, including saline and brackish waters.

The module accounts for influent flow volumes (Q_{in}), applies a calculated percent recovery ratio based on the water chemistry and treatment process used, and calculates the final volumes for both treated water (permeate, Q_{perm}) and wastewater (concentrate, Q_{conc}). Concentrate waste is always a byproduct of treatment,

Table 1
Water quality scenarios, input and output data, and model criteria used for model simulations.

Location	Seawater (Dow, 2013)	Rock Springs Uplift, Madison Fm., Wyoming (Smith et al., 2010) "Madison Brackish"	Rock Springs Uplift, Tensleep/Weber Fms., Wyoming (Smith et al., 2010)	Teapot Dome, Wyoming (Klapperich et al., 2012)
Plant type[c]	Saline Water RO	Brackish Water RO Saline Water MED and MSF	Saline and hot water >45 °C MED and MSF	Saline water RO, MED, and MSF
Formation type	*Average surface seawater*	*Brackish to saline Fm; gas reservoir*	*Brackish to saline Fm.; oil and gas reservoir*	*Brackish to saline Fm.; oil and gas reservoir*
Feed volume[a] (m^3/d)-user input	37,854 (10 mg d)	37,854 (2000–10,000[d]) (10 mg d)	37,854 (10 mg d)	6700 m^3/d
Supply TDS (mg/L) User input	*35,000*	*<1000–76,777 (Smith et al., 2010)* *Mean Brackish = 14,114* *Brine 2 = 52,852 mg/L TDS*	*<1000–101,685 (Smith et al., 2010)* *Brine 1 = 95,670 mg/L TDS*	*10,000*
Pretreatment type	Model selected	Model selected	Model selected	Model selected
Permeate % of feed volume (model calculated)	*50*	*50*[d]	*50, 75, 90*	*50*
Desired permeate TDS (mg/L) User input	<500	<500–1500	<500–1500	<500
Concentrate as % of feed volume (model calculated)	*50*	*50*[d]	*50, 25, 10*	*50*
Concentrate TDS (mg/L)	Model output	Model output	Model output	Model output
Cost to treat (US$/$m^3$)	Model output	Model output	Model output	Model output
Temperature range (°C)-user input	25	49–117 (ref (Burtner, 1987)); 25 (base case)	49–117 (ref (Burtner, 1987)); Median = 71	15–65[b] (selected range from (Klapperich et al., 2012))
Estimated cost of energy (US$/kWh)-user input or model selected	*0.07*	*0.04–0.20*	*0.04–0.20*	*0.07*
Feed pH *(ref (Smith et al., 2010))-user input*	*7*	*6.0–8.6*	*6.8–8.6*	*8.0*
Feed turbidity (NTU)-user input	*5*	*0.5–10*	*0.5–10*	*5.0*
Feed silt density index-user input	*5*	*0.5–10*	*0.5–10*	*5.0*

Italics indicate a simulation criterion.
MSF, multi-stage flash distillation (thermal process); RO, reverse osmosis; mg d, million gallons per day.
[a] Feed volume normalized to 37,854 m^3/d or 10 mg d.
[b] Lower temperature range used to illustrate effect of cooling during water storage and colder site temperatures.
[c] Plant type is selected by model based on user inputs (TDS, temperature).
[d] Base case parameters for verification of model.

except when zero-liquid-discharge (ZLD) is a disposal option (creates a solid waste product).

We used data from three proposed CO_2 storage sites in Wyoming: the Madison Fm. and the Tensleep/Weber Fms. in the Rock Springs uplift region, and data for the Teapot Dome region, following our previous studies on pretreatment and thermal treatment methods (Klapperich et al., 2012; Sullivan et al., 2013; Smith et al., 2010).

2.2. Module comparisons

Verification of a model indicates correct implementation of the conceptual model by observing consistency of response compared to real world applications and other models. We compared WTM results with the Desalination Energy Evaluation Program (DEEP) v.4.0 (IAEA, 2011). DEEP is a spreadsheet-based model that includes membrane and thermal treatment processes similar to the WTM, and has been used for treatment method and cost determinations for carbon sequestration site analysis (Klapperich et al., 2012). DEEP includes engineering-based calculations, such as capital and O&M costs, infrastructure depreciation over a project lifetime, and economies of scale for treatment. The model uses seawater treatment technologies and processes as the design basis, and optimizes desalination based on specific energy consumption (IAEA, 2011). DEEP includes different types of power plant sources (nuclear, oil and gas, coal-fired) used to supply electricity and heat for desalination, while the WTM makes no assumptions for electricity or heat sources; electricity costs and influent water temperature are

Table 2
Comparison of model features.

Key features	CO_2-PENS WTM	DEEP v. 4.0
Cost of electric power	User-selected variable, no plant source assumptions	Calculated from different plant sources
Pre- and post-treatments	User-selected variable or model assists	Included-user variable or default
RO energy recovery	User-selected variable methods	Included-fixed
Economies of scale	Stochastic ranges from literature values with scaling algorithm	Engineering calculations
Disposal	Multiple methods, stochastic ranges. User-selected, model assists	Infall/outfall cost included as % of total cost (user can modify)
Transportation	Pipeline and trucking, user-selected variable type and distances, stochastic ranges (literature)	Included as user off-on selection
Storage	Model selected, tank or pond	Not included as separate cost

Table 3
DEEP and WTM parameters chosen for verification scenarios.

Parameter	CO_2-PENS WTM	DEEP v. 4.0
Energy cost (US$/kWh)	0.04–0.20 (if fixed, 0.10)	Steam-cycle coal cost rate 1800 MWt thermal power
Desalination plant type/recovery %	Reverse osmosis/50 Multiple effect distillation/90	Reverse osmosis/calculated Multiple effect distillation/calculated
Plant capacity (m^3/d)	1700–10,000	1700–10,000
Pretreatment	User selects method Model calculates costs	$0.05/$m^3$
Transportation (km)	[a]X1 = 1.6–32 (variable) [b]X2 = X3 = 0.8	Model selected
Maximum membrane pressure (bar)	NA	69
Discount rate %	NA	5
Interest rate %	NA	5
Fuel escalation rate %	NA	3

NA, not applicable.
[a] Truck and pipeline scenarios.
[b] Pipeline only.

selected by the WTM user from reasonable or known values. Table 2 compares the features of each model. A base case of saline extracted water from the Madison Formation, in the Rock Springs uplift region of Wyoming (Table 1) was chosen for the DEEP and WTM comparison. We also use standard seawater chemistry (Table 1) (Dow, 2013) as a baseline for chemistry comparisons. Table 3 compares different parameters used for the models for the comparisons. A key difference between the models is that the WTM extracts literature cost data from many sources, and does not distinguish between capital and O&M costs, although these combined costs are sometimes used as input to the stochastic cost ranges used in model calculations. Results from the WTM are usually shown as probabilistic cost ranges per volume CO_2 stored, or per volume (m^3) influent flow (Q) basis.

We use importance analysis to show the effects of different choices for treatment on overall costs, and the tradeoffs between what might otherwise be considered unrelated segments of treatment. This applies to choices that are stochastic in nature, where a range of values is possible. The importance analysis of the input variables to the results are statistical measures computed by analyzing multiple realizations of the model in which all of the stochastic variables are simultaneously sampled for each realization of a Monte Carlo simulation. The importance measure is a metric that varies between 0 and 1 representing the fraction of the result's variance that is explained by the variable. This measure is useful in identifying nonlinear, non-monotonic relationships between an input variable and the result (which conventional correlation coefficients may not reveal). The importance measures in this study are normalized for each case so that they can be compared among different cases of interest.

2.3. Estimation of inorganic pretreatment costs

Candidate deep saline reservoirs and oil and gas reservoirs for sequestration can have very high concentrations of scaling minerals, including divalent metals (calcium, magnesium, barium, strontium), iron, bicarbonate and sulfate (Klapperich et al., 2012; Bourcier et al., 2011; Buscheck et al., 2011; Aines et al., 2011). Most literature values for antiscalent treatment are based upon either inland brackish water conditions (Gorder, 2009) or marine desalination conditions (Desalination, 2008; Wetterau, 2010) and may not reflect the full range of values that will occur in extracted waters. We used several examples ranging from brackish (Madison Fm.) to high salinity (Tensleep) waters to illustrate the effects of chemistry on inorganic pretreatment costs in the WTM (Smith et al., 2010). The DEEP model does not estimate pretreatment costs, but uses an adjustable rate for pretreatment, with a default setting of $0.05/$m^3$ (O&M chemical costs only). This rate is higher than some outside compiled estimates (Desalination, 2008), and higher than generic pretreatment cost rates evaluated from literature values in the WTM, and thus is a conservative estimate. Using a conservative value is appropriate for the types of waters that might be extracted during carbon storage.

2.4. Estimation of organic pretreatment costs

The WTM uses literature-based cost ranges for various organic pretreatment technologies, including adsorption, oxidation, filtration, zeolite treatments, activated carbon, and chemical treatments (e.g., lime). Costs may vary widely on a site-to-site basis, and so a truncated probability cost curve with an appropriate median value is used to provide a probabilistic range for organic pretreatment, without the need for site-specific organic concentration data. This analysis is particularly useful for preliminary site evaluations, because little organic speciation or concentration information is known in most cases. Fig. 3 shows ranges and medians for organic pretreatment costs gathered from the literature, along with an example of the truncated probability curve used by the WTM to estimate the most likely range of pretreatment costs for unknown concentrations of organic constituents. Low median values for some of the methods indicate that more sources were found with the lower costs, partially because of cost reductions over time as treatments have become more efficient. The use of the probability curve allows the user to best estimate the cost ranges of organic pretreatment without knowing the exact composition of the extracted water; the curve also can be used to estimate probabilities of costs changing when composition changes. This may occur, for example, when an extraction well is pumped for a long time. The DEEP model does not specifically address organic pretreatment, although these costs could be considered part of the generic cost of pretreatment along with inorganic pretreatments.

3. Results

3.1. Module verification – energy costs

Energy costs comprise approximately 50% of most seawater membrane (RO) treatment plant costs (Fritzmann et al., 2007; Bourcier et al., 2011; Desalination, 2008). Fig. 4a and b shows a comparison between specific energy costs in US$ for a range of volumes treated per day (m^3/d) using the DEEP model and the WTM module for two CCUS scenarios, the Madison Fm. (brackish range, mean TDS ~ 14,000 mg/L), Madison Fm. Brine 1 (high range TDS ~ 75,000 mg/L) (Fig. 4a), and for typical seawater (Fig. 4b). Assumptions for these WTM model runs for simplified scenarios included a 50% recovery goal with no organic pretreatment, transportation, or storage. The WTM data includes various options for pressure energy recovery, such as Pelton turbines, and a no-recovery option; energy recovery is implicit in the DEEP calculations. The WTM returns both RO and thermal results in Fig. 4a; the brackish water is treated by RO, while the brine is treated by thermal methods. The term "generic" refers to pretreatment scenario used; salinities for each case are shown in Fig. 4a legend. Specific electricity costs (DEEP) are US$0.24/$m^3$ for seawater (42% recovery ratio), and US$0.16/$m^3$ for the Madison Fm. (14,000 mg/L TDS and 77% recovery ratio). Specific costs for seawater calculated

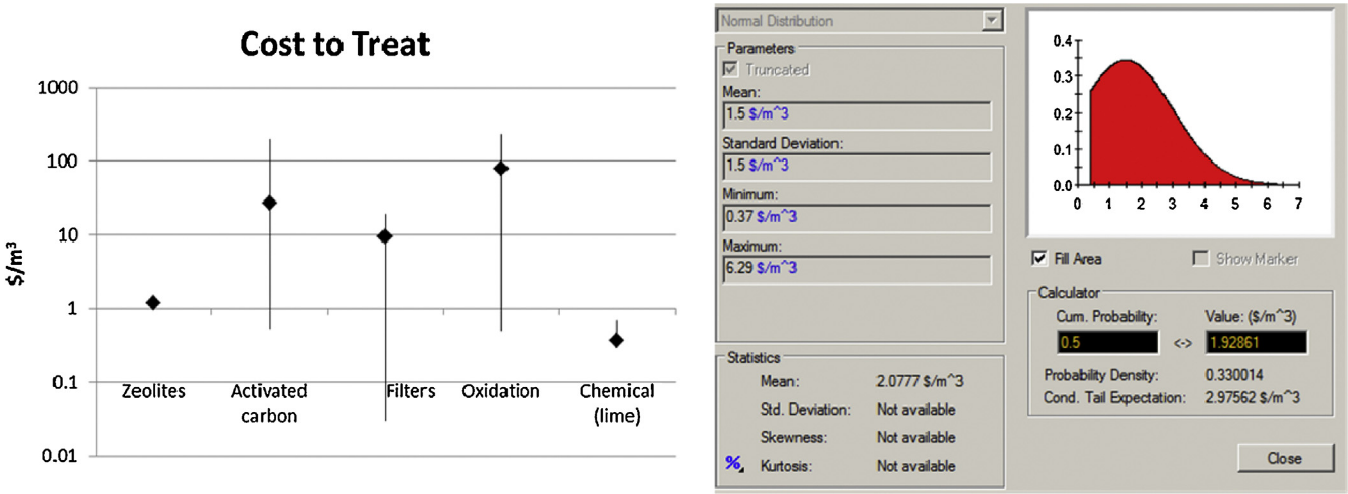

Fig. 3. Literature cost ranges of various organic pretreatment methods (◊ are medians) (left), and an example truncated probability curve as a solution to wide variations and site specificity in organic pretreatment costs (right).

by the WTM are US\$0.19/m^3; and \$0.076/m^3 for the Madison Fm. (14,000 mg/L case). Computations were run for the Tensleep Fm. Brine 2 (TDS = 108,740 mg/L); however, the results were the same as for the Madison Fm. brine (Tensleep results not shown). This occurs because the WTM defaults to thermal treatment methods when the salinity exceeds 35,000 mg/L TDS (in common for both waters), and thermal treatment electrical costs are predominantly related to pumping, not salinity.

Electricity costs presented here are model-calculated for membrane (RO) methods only; WTM does not calculate separate electricity costs for thermal methods. Borsani and Rebagliati (2005) discuss methods for estimating costs for thermal plants (MSF, MED) as well as RO plants. They calculated that specific costs for electric power in treatment plants (seawater; 2005 US\$), based on a US\$0.03/kWh electricity cost, would be between \$0.10–0.15/m^3 (\$0.12–0.18; 2013 US\$) (Table 4); this implies electricity cost percentages of 23% of total plant costs for MSF, 19% for MED, and 33% for RO. When these ratios are applied to total treatment costs from the WTM, MED and MSF electricity costs are very close to those calculated by DEEP for a steam-cycle coal-fired power plant (Table 4). DEEP arrives at power costs based upon user-selected characteristics of the power source to be used for desalination (e.g., coal, nuclear, steam cycle, gas cycle, etc.). A steam-cycle, coal-fired plant creates electricity at a modeled cost of US\$0.076/kWh, more than double the electricity cost used by Borsani and Rebagliati (2005). For Madison Fm. brackish (TDS ~ 14,000 mg/L) water, this leads to a specific electricity cost of US\$0.155/m^3 (15% of plant operating costs at 1000 m^3/d, up to 30% at 8000 m^3/d); for seawater, the specific electricity cost is US\$0.20/m^3 (20% of operating costs at 1000 m^3/d, up to 35% at 8000 m^3/d).

3.2. Transportation costs

We show a sensitivity analysis for both models in Fig. 5. The DEEP model estimates transportation costs using a percentage of total treatment costs, while the WTM model takes user input information. The WTM model produces cost variations shown as median values derived from the full stochastic output distributions (not shown in Fig. 5). For simplicity, the base WTM scenario was evaluated using either all trucking or all pipelines for transportation segments X1, X2, and X3 (Fig. 2). Distances were varied from 0.8–32 km for the X1 transportation segment (Fig. 2). The constant value of 0.8 km was used for X2 and X3 segments. Transportation adds considerably to costs for the DEEP results below 4000 m^3/d capacity, with maximum costs near \$10/m^3 at Q = 1000 m^3/d, compared to \$2/m^3 for treatment with no transportation.

3.3. Inorganic pretreatment

A cross-check of seawater chemistry between the two WTM inorganic pretreatment modes (generic literature costs vs. specific scaling potential calculations) yielded near-identical mean results (not shown). This supports the WTM generic scenario costs which are based on seawater desalination references. Fig. 6a shows the sensitivity of the DEEP model to pretreatment cost variations. DEEP is dependent upon user cost input, while the WTM depends upon specific chemistry input values. Fig. 6b shows mean pretreatment costs calculated with the WTM using various input chemistry values, including the Madison Fm. (~14,000 mg/L), seawater, and Brine 1 and Brine 2 (Table 1). The WTM is not designed to provide cost reductions for increased pretreatment volumes. The seawater example has the lowest pretreatment costs, converging with the DEEP model at higher capacities. The Madison Fm. and the two brine samples are more costly to treat based on input geochemistry values.

3.4. Organic pretreatment

Organic pretreatment costs can be significant with respect to overall treatment costs. Fig. 7 shows a comparison between a Teapot Dome base case (Table 1) without organic pretreatment (left chart), and with organic pretreatment (right chart). Without pretreatment, costs for membrane desalination range from \$0.45/m^3 to \$13/m^3, and is primarily dependent upon the concentrate disposal method chosen by the model. The addition of organic pretreatments increases the range of potential costs for both membrane treatments (shown below the 45 °C source water temperature cutoff) and thermal methods (>45 °C). Costs increase up to \$17/m^3 for membrane methods, and up to \$12/m^3 for thermal methods in the most extreme scenarios. Median costs for treatment including organic pretreatments were found to be \$2.33/m^3 (S.D. ±1.138, n = 297) for membrane methods, and \$3.10/m^3 (S.D. ±1.08, n = 203) for thermal methods, without additional disposal costs.

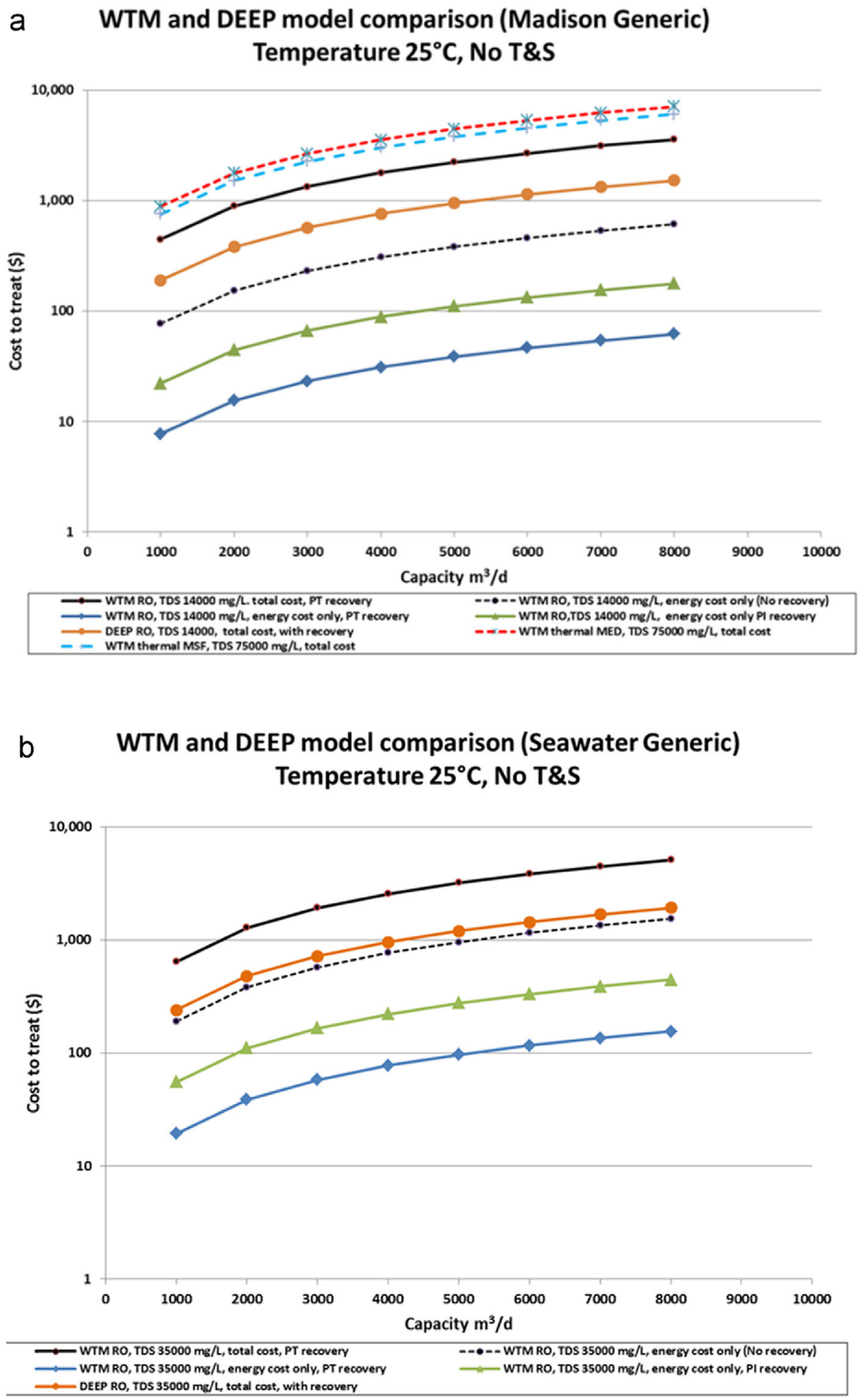

Fig. 4. (a) WTM vs. DEEP model results for RO and thermal (MED and MSF) treatment cost analysis of Madison Fm. chemistry. Costs from the WTM are: (1) total costs excluding transport and storage cost; (2) energy costs alone without additional energy recovery, and (3) energy costs with recovery methods (Pelton Turbine and Piston Isobaric). "Generic" refers to pretreatment type; salinities are listed for each scenario. (b) WTM vs. DEEP for seawater, cost comparisons for RO treatment. Costs from the WTM are: (1) total costs excluding transport and storage cost; (2) energy costs alone without additional energy recovery, and (3) energy costs with energy recovery methods (Pelton Turbine and Piston Isobaric). Generic refers to pretreatment type.

4. Discussion

4.1. Energy use and recovery

For thermal treatment methods, the cost of energy is included as electricity for pumping, and as thermal heat for evaporative effects. Specific electricity costs are lower for thermal methods than for RO, because only low-pressure pumping is needed. The WTM thermal electrical using estimations of the fraction of total electricity costs compare well with costs calculated by the DEEP model (Table 4).

Energy recovery is now a standard for all newer RO systems. The WTM calculates a greater energy savings (cost reduction) for each of the energy recovery methods than does the DEEP model. The wide variation in specific costs indicates that the WTM methodology

Table 4
Comparison of electricity costs per volume of water treated.

	WTM			Borsani and Rebagliati			DEEP (coal, steam cycle)		
	RO	MED calculated	MSF calculated	RO	MED	MSF	RO	MED	MSF
Power cost ($/kWh)	0.07	0.07	0.07	0.03	0.03	0.03	0.076	0.076	0.076
Seawater case ($/m^3)	0.19	0.12	0.15	0.15	0.10 (0.12)[a]	0.12 (0.15)[a]	0.24	0.12	0.16
Madison Fm. caseTDS ~ 14,000 mg/L($/m^3)	0.076	0.084–0.22	0.10–0.26	N/A	N/A	N/A	0.16	0.12	0.16

N/A, not applicable.
[a] Values in parentheses are corrected to 2013 US$ via inflation index. Plant size for calculations – 10,000 m^3/d, except: Borsani and Rebagliati: MSF and MED – 58,000 m^3/h.

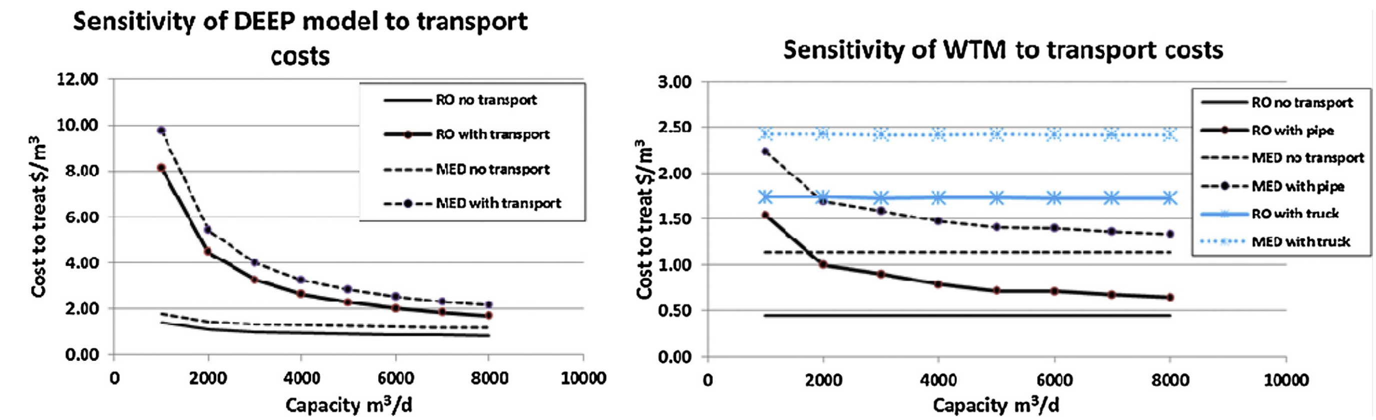

Fig. 5. Sensitivity of DEEP (left) and WTM (right) to transportation choices for the Madison Fm., generic pretreatment case. Conditions include TDS = 14,000 mg/L; T = 15–45 °C for RO, 45–65 °C for thermal treatments.

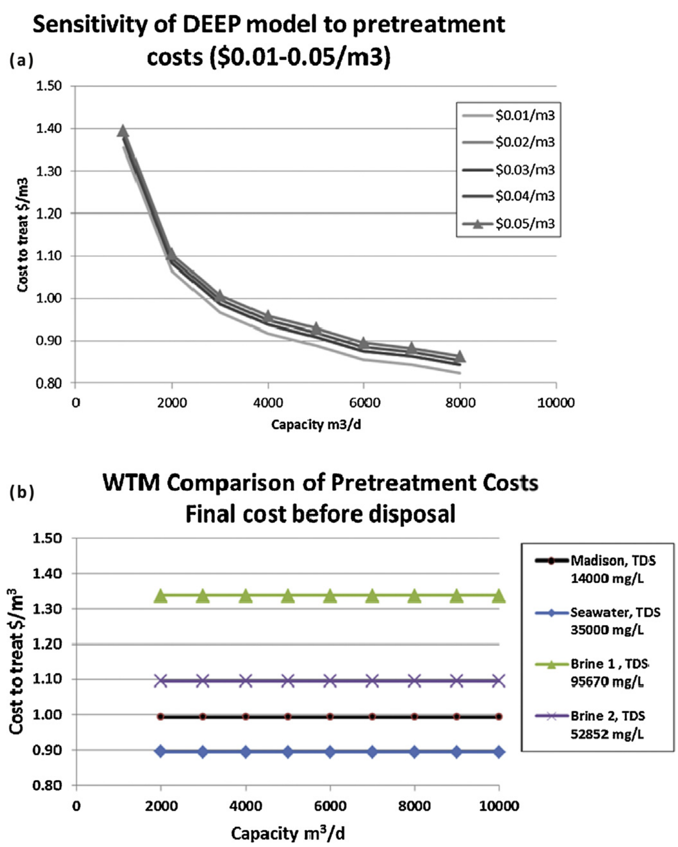

Fig. 6. (a) Sensitivity of DEEP model to pretreatment cost variations. DEEP is dependent upon user cost input, WTM depends upon specific chemistry input values. Generic pretreatment Madison Fm. scenario, no transportation, storage or disposal included. (b) Mean pretreatment costs effects in WTM for various input chemistries, including Madison Fm., seawater, and two brine examples.

may estimate larger savings via energy recovery; this is device-dependent and based upon manufacturers reported savings.

4.2. Transportation-model comparisons and importance analysis

Within WTM, truck transportation costs are based on a fixed cost/volume; the only variation is in transportation distance. No economy of scale occurs with truck transportation. Here, stochastic variation from distances describes the deviation from the mean. Pipelines enjoy steep cost reductions through economics of scale; broadly, pipeline construction costs are linearly related to pipe diameter whereas flow in the pipeline increases exponentially (Middleton, 2013).

The DEEP transportation costs compare well with the WTM costs when no transportation is included, and at higher Q values (>4000 m^3/d) (Fig. 5). However, deviation from the WTM results reached 5 times the costs at lower flow rates. This cost effect far exceeds the economy of scale evident in the no-transportation case calculated by DEEP. This is likely because dividing overall treatment costs by smaller flow volumes in the DEEP spreadsheet increases the relative effect of the transport percentage. A similar effect has been observed in some WTM simulations. The DEEP results compare well with the WTM cost calculation methods for no-transport and higher-volume transport scenarios. DEEP may overestimate transportation costs per volume at low volumes.

We used WTM to evaluate the relative importance of the two types of transportation versus other stochastic inputs for the fixed-salinity base case (Madison Fm., TDS ~ 14,000 mg/L, Fig. 8). Four disposal scenarios were selected by the model. Base-case inputs considered were pretreatment costs including acid and antiscalent, feed temperature, feed pH, and concentrate disposal costs arrayed by concentrate disposal method. Disposal method is an important consideration related to transportation, because concentrate disposal is almost always needed, and because appropriate concentrate disposal may not exist at the treatment site, implying a dependence upon distance to a disposal location. Note that for all importance analyses the y-axis refers to cost importance.

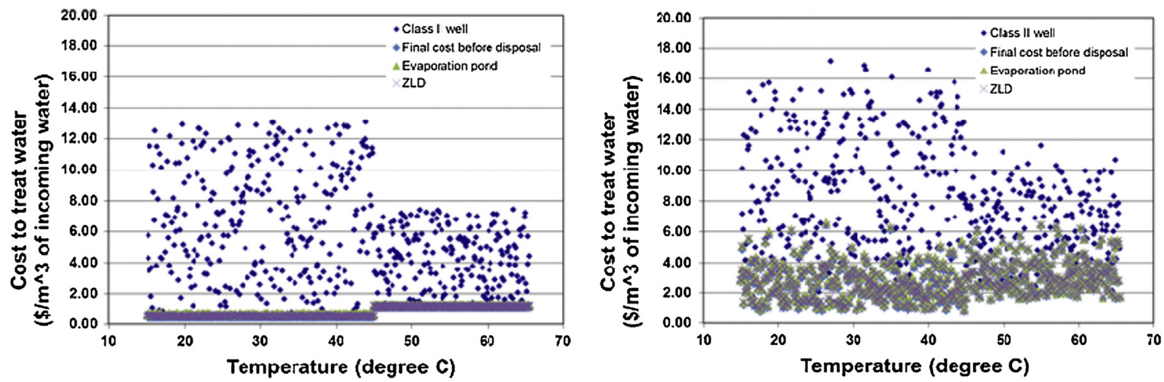

Fig. 7. Effect of no organic pretreatment (left) versus adding organic pretreatment (right) to overall costs for a Teapot Dome case, shown versus source water temperature (°C) and plotted for four concentrate disposal methods.

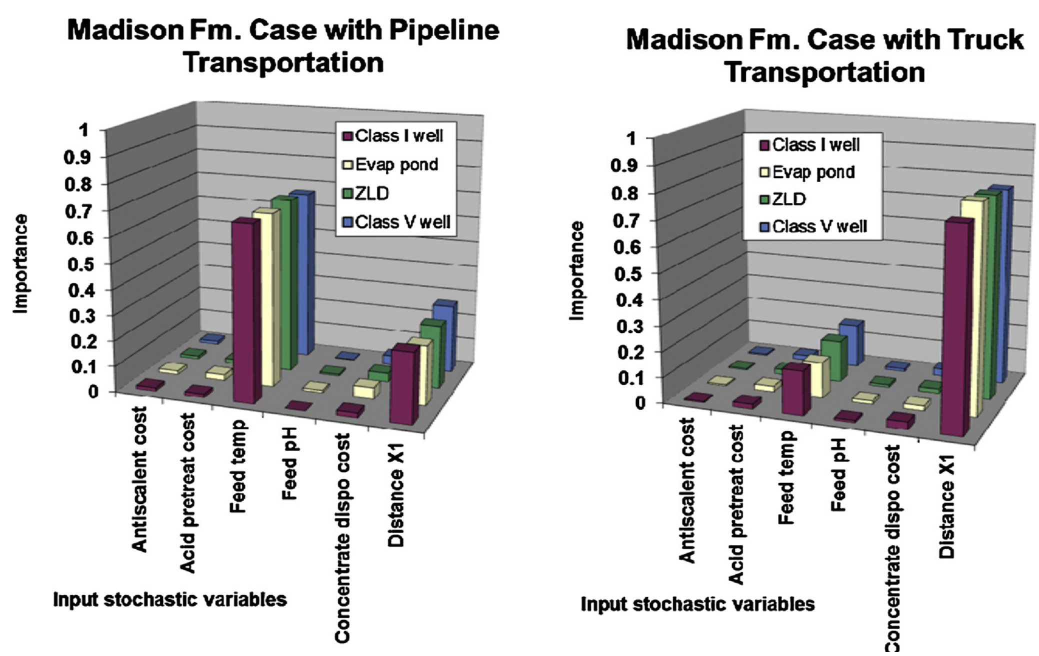

Fig. 8. Importance analysis comparison of pipeline (left) and truck (right) transportation versus other WTM stochastic parameters. Conditions include TDS = 14,000 mg/L; T = 15–45 °C for RO, 45–65 °C for thermal methods. Disposal conditions do not include Class II well option for simplicity.

For pipeline transportation, feed temperature was the most important factor related to costs, followed by transportation distance. Feed temperature controls the selection of treatment method in WTM. Thermal methods are selected at high temperatures >45 °C because of potential damage to RO or NF membranes. Higher temperature feed also implies cost savings for thermal methods. The combination of these factors indicates that it is worth locating thermal treatment facilities closer to hot water sources, where heat can be better conserved and used in treatment, regardless of the distance to permeate use and concentrate disposal locations. For truck transportation, a greater importance is placed on distance than on feed temperature. If truck transportation is used, reducing distances between source, treatment, and use is critical to cost management, with a lower priority on thermal treatment methods.

In a second analysis, we include only one disposal method (Class I well) for simplicity, but include both tank and pond storage options (Fig. 9). When truck transportation is used, distance remains the most important contributor to costs; pond storage is second followed by feed temperature. Pond storage is most important when pipeline transport is used. At high volumes, and for more permanent installations, pond storage is usually necessary. If combined with truck transportation, we see that treatment location, volume, and storage may combine to dominate a cost profile regardless of treatment method or even economies of scale. Interestingly, we found that pond storage tended to be more expensive on a per volume basis than transport costs ($3.00/m^3 to store vs. $1.24/m^3 to transport); however, the cost of transportation by truck has a higher standard deviation per volume and thus exerts more influence on overall cost variation.

4.3. Inorganic pretreatment effects on costs

Brines (waters with salinities greater than seawater) can be expected to have complex geochemistry (Bourcier et al., 2011), and, thus, more complex or expensive pretreatment processes will be needed to prevent formation of mineral scale. This is particularly true for membrane processes; but also is possible for thermal treatments of inland (non-marine) waters. The WTM is designed to consider the basic inorganic geochemistry of a water sample when calculating pretreatment costs. Fig. 6b illustrates the effects of complex geochemistry on the cost model. The least-cost geochemistry (seawater) converges with the DEEP model, validating the treatment assumptions at higher volumes. At lower volumes, DEEP estimates higher costs/volume. This is driven par-

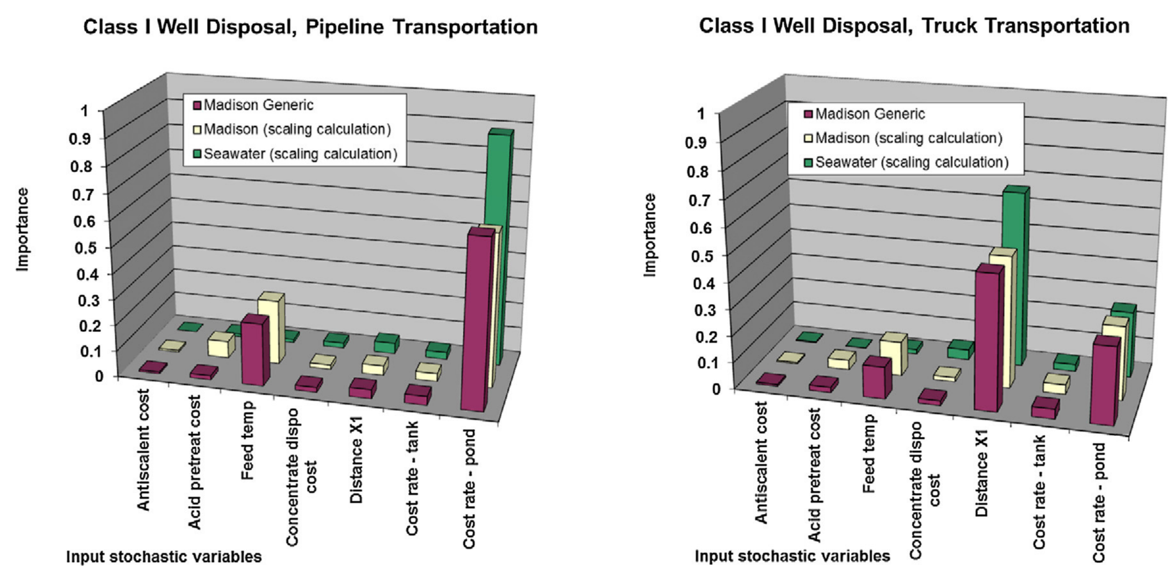

Fig. 9. Importance analysis comparing WTM stochastic inputs for three different water chemistry cases. Class I well disposal was selected for simplicity of comparison. Pipeline transportation is shown on left, truck transportation on right. Generic and scaling calculations refer to pretreatment scenarios.

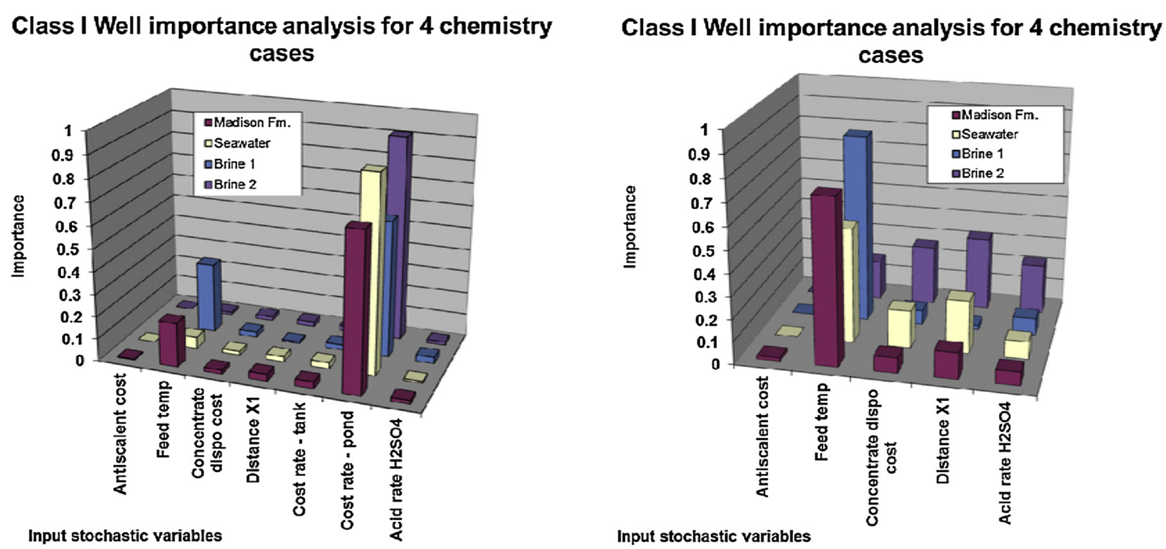

Fig. 10. Importance analysis for several different water chemistries, including two brine samples. For simplicity, produced water options were not included, and Class I well disposal was chosen. Waters are from Table 1.

tially by the cost calculations in DEEP but also by division by smaller volumes.

Fig. 10 shows an importance analysis for four cases (Madison Fm. brackish water, seawater, and two brines, Table 1). We included Class I well disposal, pipeline transportation, and storage options, but no produced water or class II well disposal. Fig. 10 (left) compares all of the stochastic process results. Pond storage is clearly the most significant contributor to cost variance, followed by feed temperature. Given this result, we conclude that volume management is a critical feature of these systems. Fig. 10 (right) shows the comparison without storage included. Among the remaining variables, feed temperature contributes the most to variance for the lower salinity samples. Temperature figures into the cost calculations in the WTM in two places: scaling factor calculations that determine additive (antiscalent and acid) costs, and as the determining factor separating membrane treatments from thermal treatments. Thermal treatments tend to cost more in terms of energy used, but have less cost from pretreatment. We note that Brine 2 costs are more dependent upon distance, acid cost rates, and disposal rates, factors related to the higher scaling potential of that brine fluid chemistry (Klapperich et al., 2012).

4.4. Effects of organic pretreatment on overall costs

While specific concentration and chemistry data and subsequent rigorous engineering design specifications are the most desirable scenario for understanding organic pretreatment costs, our interpretation of the literature ranges for an unconstrained system indicates that these costs can be estimated for a generalized case, and can create a significant influence on overall costs. This analysis is particularly important for source waters that originate from EOR or from “uneconomic” brackish and saline reservoirs (where residual organics, but not economically recoverable hydrocarbons, exist). An importance analysis of organic pretreatment costs versus other stochastic variables is shown in Fig. 11. We used produced water as the water type for this analysis because EOR waters are regulated and handled

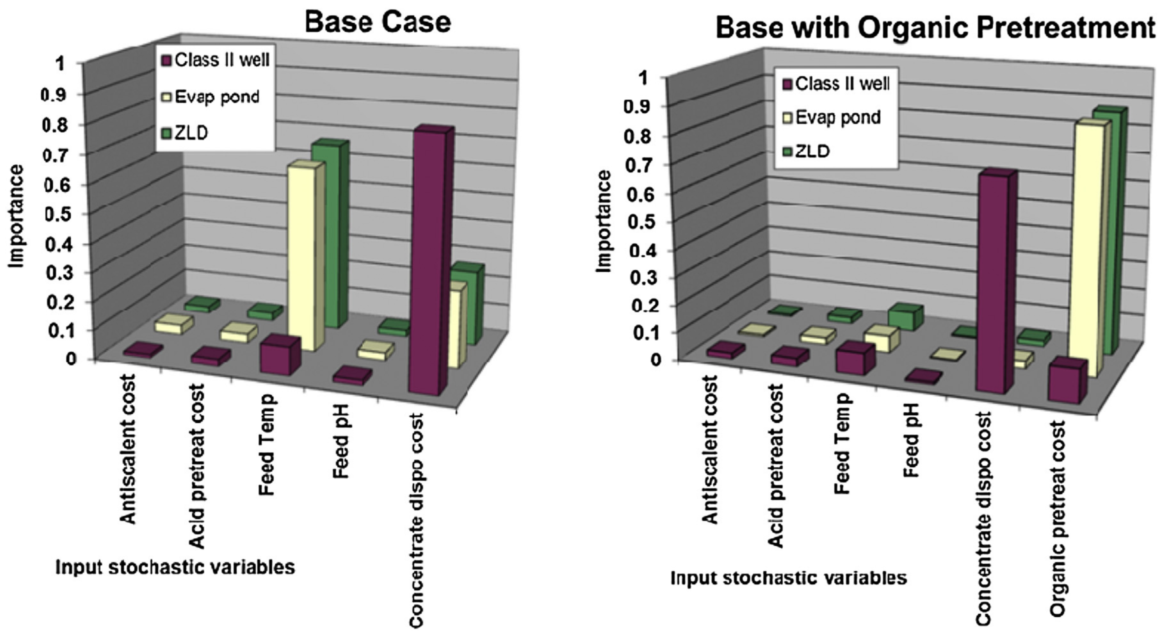

Fig. 11. Importance analysis of stochastic parameters used to calculate a Teapot Dome base case (left, no organic pretreatment) and a case with organic pretreatment (right). Note, median cost for activated carbon is the median chosen for modeling scenarios in this paper. Low values reflect changes in costs over time as systems become more efficient.

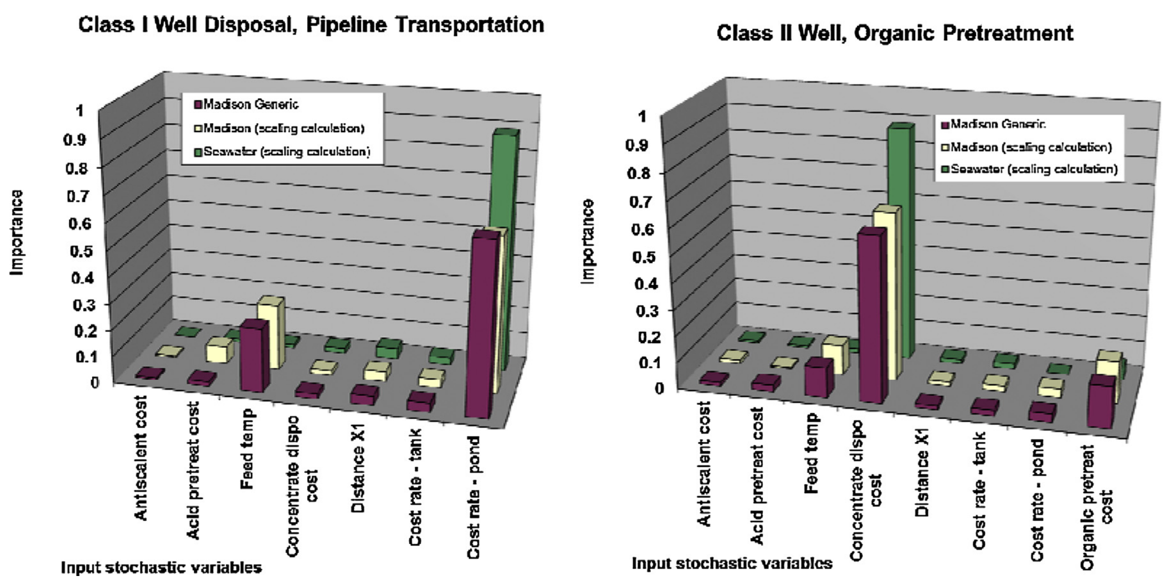

Fig. 12. Comparison of importance cases from Fig. 9 (Madison Fm. pipeline transport case) with the same case treated as an EOR (produced) water type. Generic and scaling calculation refers to pretreatment scenario.

as produced water. When organic pretreatment is added to a base case scenario, these costs became more important to the total cost profile than feed temperature and concentrate disposal costs, except for Class II well concentrate disposal cases. Because of regulation, produced water concentrate disposal in the WTM is limited to evaporation pond, zero-liquid discharge, or a Class II well. Because Class II well disposal has a very wide range of potential costs in the literature (from <\$0.01 to >\$10.00/m^3), this disposal method remains a large contributor to costs and to cost variance regardless of other contributors to treatment costs (Acharya et al., 2011; Boysen et al., 2003). Otherwise, feed temperature is the secondary cost variance driver. Modeling waters that are not defined as "produced" for the purposes of the model will result in much lower variance in the concentrate disposal parameter.

We also considered the importance of organic pretreatment in relation to transportation and storage in an EOR scenario (Produced water type, Class II well disposal, organic pretreatment included). There is a large potential for cost divergence from the base case (non-EOR). This is illustrated in Fig. 12, where organic pretreatment and concentrate disposal change importance relative to feed temperature and pond storage costs. In Fig. 9 (left side), we show the truck transportation variant of this scenario. We note that storage, transportation to disposal sites, and concentrate disposal cost estimation is complex and volume dependent. The comparisons illustrate the tradeoffs that may need to be considered when analyzing cost scenarios that include transportation, disposal, and storage for EOR or produced waters.

5. Conclusions

Water treatment is becoming a significant contributor to costs for energy production and extraction. There is significant potential for extracted water treatment processes and costs to be poorly understood and underestimated utilizing current models. Comprehensive system analysis models can reduce the potential risk of ignoring significant costs related to treatment and transportation. The WTM includes both primary and secondary processes in a treatment train that can be used to show the interconnections between process choices and costs, specifically for underestimated parameters like organic pretreatments, transportation, and storage. Monte Carlo capabilities and sensitivity analysis allow the user to better understand tradeoffs when planning for treatment of waters that are not similar to seawater, and in cases where specific site chemistry data are not available.

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