BRIDGING THE GAP BETWEEN PRODUCED WATER AND SOURCE WATER: AN ECONOMIC ANALYSIS OF PRODUCED WATER TREATMENT

A Thesis

by

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ABSTRACT

Accumulating seismicity and groundwater contamination concerns are fueling increased regulations that can significantly burden an exploration and production (E&P) company's water management budget – especially in a low-cost market. The goal of this research is to evaluate the economics of oil and gas produced water (PW) treatment and reuse as an alternative to injection well disposal. The primary objectives are: 1) determine general field conditions that economically favor treatment and reuse, 2) compare the relative economics between mobile (on-site) and centralized treatment, 3) evaluate pipeline versus trucking transportation and 4) assess zero liquid discharge (ZLD) treatment technology feasibility.

The model, built to address the objectives, functions as a PW management planning and decision support tool for an operator. For input field conditions, the model simulates disposal and treatment and reuse – comparing mobile versus centralized treatment. Trucking and pipeline conveyance are evaluated for centralized treatment transportation. The model outputs the net water management cost and operator breakeven treatment cost (OBE) for each scenario. The OBE is the cost of treatment for which the economics of injection disposal and treatment and reuse are equal. When a service company's treatment cost is less than or equal to the OBE, treatment and reuse is feasible.

A sensitivity analysis identified the primary economic drivers. The observed effects of each driver on the OBE indicate conditions that promote treatment and reuse. These conditions include long distances, high treatment recoveries, high injection costs and long project lifespans. Relative economics favor on-site treatment and reuse for long distances, high treatment recoveries, low project lifespans and an increase in pipeline cost. The opposite is observed for centralized with pipeline. The model simulated for the Texas Permian Basin. Results demonstrate the use of the model and provide insights into the potential for Permian Basin water cost savings.

DEDICATION

The following work is dedicated to my family – Grandpa, who encouraged me to pursue engineering; Grandma, who continues to inspire me each and every day to push through any obstacle; and my loving parents for their support through thick and thin.

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Contributors

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All work for the thesis was completed by the student, under the advisement of David Burnett of the Harold Vance Department of Petroleum Engineering.

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NOMENCLATURE

APB	Acid producing bacteria
API	Application program interface
bbl	Barrel of oil; 42 gallons
BTEX	Benzene, toluene, ethylbenzene and xylene
CAPEX	Capital expenditure
ClO_2	Chlorine dioxide
DGF	Dissolved gas flotation
E&P	Exploration and production
GPRI	Global Petroleum Research Institute
H_2S	Hydrogen sulfide
HC	Hydrocarbon
HDPE	High-density polyethylene
IGF	Induced gas flotation
IRB	Iron reducing bacteria
JSON	JavaScript Object Notation
MED	Multiple-effect distillation
MF	Microfiltration
MILFP	Mixed-integer linear fractional programming
MSF	Multi-stage flash distillation
NDP	Naphthalene, phenantherene and dibenzothiophene

NF	Nanofiltration
NORM	Naturally occurring radioactive material
NPDES	National Pollutant Discharge Elimination System
OBE	Operator breakeven treatment cost
$OBEC_P$	OBE for centralized with pipeline conventional treatment
$OBEC_T$	OBE for centralized with trucking conventional treatment
OBEM	OBE for mobile conventional treatment
OBEZC	OBE for centralized ZLD treatment
$OBEZC_P$	OBE for centralized with pipeline ZLD treatment
OBEZM	OBE for mobile ZLD treatment
OPEX	Operating expenditure
P10	Low estimate; 90% of calculated estimates are above this value
P50	Mean; 50% of calculated estimates are above this value
P90	High estimate; 10% of calculated estimates are above this value
PAH	Polycyclic aromatic hydrocarbons
POTW	Publically owned treatment works
ppm	Parts per million (milligram per liter)
PW	Produced water
RO	Reverse osmosis
SCBE	Service company breakeven treatment cost
SRB	Sulfate reducing bacteria
SWD	Salt water disposal well

TDS	Total dissolved solids
TOC	Total organic carbon
TSS	Total suspended solids
UDT	User defined data type
UF	Ultrafiltration
UIC	Underground Injection Control
URL	Uniform resource location; web address
US	United States
USEPA	United States Environmental Protection Agency
USGA	United States Geological Survey
VBA	Visual Basic for Applications
VCD	Vapor compression distillation
ZLD	Zero liquid discharge

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1. INTRODUCTION

1.1 Problem statement

Throughout the lifetime of oil and gas wells, a combination of oil, gas and water are produced. Water is the largest byproduct of this production (SPE 2011). With the growth in development of unconventional resources in the exploration and production (E&P) industry, the use of hydraulic fracturing has increased water consumption enormously and brought major public attention to water in the industry. On average, 0.5 to 10 million gallons of water are used per well to fracture, and 20 to 40% of this volume resurfaces in just a few weeks (Kondash, Albright, and Vengosh 2017, Marcellus-Shale 2011). This initial water is commonly termed flowback, whereas additional water during production is defined as produced water (PW). As PW volumes can often exceed that of flowback, no distinction will be made in this paper, and any water surfaced during E&P operations is classified as PW. With these massive volumes, water management and disposal is often a significant portion of an upstream company's lease operating expense (Administration 2016). With seismicity concerns and potential disposal well capacity limitations, companies are considering unconventional water management options, such as treatment and reuse, to reduce costs and relieve the industry's burden on local water sources (Jacobs 2016).

The potential economic viability of PW treatment and reuse is a popular topic discussed and presented recently by many (Collins 2016, Dunkel 2016, Jacobs 2016, Ruyle 2015, Schilling 2016, Teague 2016). While the claim that PW treatment and reuse can save a company money is common, there exists little quantitative data or analyses on the subject. Many of these articles present site-specific examples or make broad claims. The idea of connecting a waste from production to the water consumption needs in drilling and completion operations does exist. However, the economics must be favorable for this idea to become a reality.

Several produced water models have been documented in literature (AQWATEC 2016, Gao and You 2015, Lira-Barragán et al. 2016, Robart 2012, Slutz et al. 2012). Of these models, two have been economic and have merely presented case studies using their models in shale water management (Robart 2012, Slutz et al. 2012). The others have discussed either uncertainty and optimization or determination of treatment technology and beneficial use.

Significant uncertainties remain in PW economics. Conventionally, salt water disposal well (SWD) injection is the most popular and economic form of PW management (McCurdy 2011, Veil 2015). Treatment companies struggle to understand the market, the field conditions that favor treatment over SWD injection and application of treatment technologies – most of which are currently mobile skids. As treatment has become mobile to adapt to the nomadic nature of the upstream oil and gas industry, an additional uncertainty exists as treatment can either occur on-site (mobile skid at each well) or at a centralized location (multiple skids at one site). Another popular subject is transportation – often the most expensive portion of water management. Trucking is the conventional method; however, it is possible that pipeline infrastructure can economically compete with trucking and provide greater social benefits, such as reduction in traffic, road damage and accidents (Collins 2016, Dunkel 2016, Jacobs

2016, Schilling 2016). Economics for pipelines have been presented in specific cases, yet an overall economic comparison has not been analyzed in literature. Uncertainty with respect to pipelines and trucking still exists. Another uncertainty is in application of zero liquid discharge (ZLD) technologies that evaporate the entire feed water and produce a solid waste. Some companies claim the captured salt has potential sellable value for applications such as road salt. These systems usually require massive energy input and can cost much more than other treatment technologies. The tradeoff between high treatment cost and producing a valuable salt and water product has not yet been explored.

These uncertainties were observed in published literature and field experience from members of the Global Petroleum Research Institute (GPRI) team. The GPRI team members have more than 20 years of experience in the PW treatment sector and understand the knowledge gaps that exist. The goal of this project is to address these uncertainties by development of an economic model based on past GPRI experience coupled with industry input and available knowledge in literature.

1.2 Objectives

The following research objectives are defined from the uncertainties discussed in the problem statement:

1. Determine general field conditions that favor treatment and reuse over injection well disposal.

2. Analyze the relative economics between mobile (on-site) and centralized treatment and reuse.
3. Evaluate pipeline infrastructure versus trucking.
4. Investigate the feasibility of a ZLD treatment approach.

1.3 Approach

A model was developed to accomplish these objectives. Analytical models, composed of mathematical algorithms, are used to simulate real-world systems and processes. Models can be used to simulate potential conditions that can occur in the field in order to understand "what-if" scenarios and potential risk. Thus, the goal was to develop and analyze a model that is simple in design but accurately represents the significant costs of PW management.

The model considers multiple PW management scenarios from an operator's perspective for input field conditions. In oil and gas, an operator is the entity who manages the exploration, production and development of a well or lease. Generally, this is the company funding the project and making the overall decisions. Viewing the economics from the operator's perspective provides insights into the significant financial components of PW management.

The specific scenarios that are simulated include SWD injection, mobile (on-site) and centralized treatment and reuse. Pipeline and trucking transportation are considered for a centralized approach. Outputs include total and net management costs for each scenario. An operator breakeven treatment cost (OBE) is defined and used as a metric to evaluate PW treatment economics. The OBE is the specific treatment cost in dollars per barrel ($/bbl) that makes the net treatment and reuse cost equal to the total SWD injection cost. The OBE is important as it provides the maximum treatment cost per barrel that a service company can charge and remain competitive with SWD injection. A higher OBE is desired as this increases the probability of an achievable treatment cost. An OBE ratio of centralized (OBEC), with both trucking and pipeline, to mobile (OBEM) is defined to serve as a metric in evaluating relative economics. When the ratio is greater than one, centralized is preferred; at a ratio less than one, mobile is preferred. A similar OBE ratio is also defined for ZLD to conventional treatment to serve as a metric in evaluating feasibility of ZLD treatment.

The model was evaluated with a sensitivity and uncertainty analysis to address the research objectives. The sensitivity analysis was used to determine the most significant variables, indicating the primary economic drivers, for each of the outputs. A Monte Carlo simulation was used for the uncertainty analysis. The inputs for each variable were subjective probability distributions based on experience and literature. The simulation was iterated through 100,000 times and provided probability distributions for each of the outputs. By observing the sensitivity and uncertainty analysis results, conclusions were drawn to support each of the research objectives.

2. LITERATURE REVIEW

The following literature review discusses PW volumes, characteristics, regulations, treatment technologies, costs and models. As will be discussed in Section 3, this model only considers economics and does not consider specific treatment technologies nor consider input water quality. However, it is important to understand treatment technologies and PW characteristics in order to contextualize the treatment and source water costs discussed in further sections.

2.1 Produced water

PW is the water that is produced along with the desired hydrocarbons after completion during the production phase of a well. Recall from the problem statement (Section 1.1) that no distinction is made between PW and flowback water in this paper. A typical well will produce water throughout its entire lifetime; although unconventional wells typically produce at lower water cuts than from conventional wells. PW is formation water, injected water or a mixture of the two, and its quality often changes over time. It usually contains dissolved and suspended, inorganic and organic, formation-inherent constituents mixed with chemicals used in the injected water. Water quality and volume produced varies by geologic location, type of hydrocarbon-bearing formation and specific time during the life of the well (Veil 2015). Throughout this paper, flowback will not be distinguished from PW and is considered merely a portion of PW.

2.2 PW volumes

In 2012, 20.6 billion barrels (865.2 billion gallons) of PW were generated onshore in the 31 U.S. oil and gas producing states (Veil 2015). In order to put this into perspective, the reported PW volume can be compared with the daily water demand of irrigation. In 2010, the total United States (US) water source withdrawals for irrigation was 115 billion gallons per day (Maupin et al. 2014). Therefore, the total 2012 PW volume generated was only 7.5 days of the US irrigation water demand in 2010.

Horizontal drilling and multi-stage hydraulic fracturing have made unconventional, tight reservoirs accessible. The water production from these reservoirs is often initially high and declines over time. Thus, the decline curve methodology for oil production proposed by Arps (1945) has been used to model water production (Arps 1945, Bai, Goodwin, and Carlson 2013, Kondash, Albright, and Vengosh 2017).

Kondash, Albright, and Vengosh (2017) conducted a study using water production data from DrillingInfo to generate decline curves for the Bakken, Barnett, Eagle Ford gas and oil, Haynesville and Niobrara basins. They also developed curves for Marcellus and Monterey from state website data. Findings of this study include mean total water production values per well for the Bakken, Barnett, Eagle Ford gas and oil, Haynesville, Marcellus, Monterey and Niobrara basins as follows: 144,000; 182,000; 126,000; 426,000; 111,000; 25,000; 178,000 and 116,000 bbls.

2.3 PW quality

In addition to fluctuating volumes and production rates from individual wells and basins, PW contents are also highly variable and often contain an amalgamation of dissolved inorganics, dissolved and suspended organics, injection chemicals and organic and inorganic solids. The concentrations of these constituents may vary with time, well, formation and location. It is important to understand the general components of PW as this will determine treatment technologies required.

2.3.1 Inorganics

The dissolved inorganic content of PW consists of various ions, trace metals and naturally occurring radioactive material (NORM). Dissolved ions contain a wide range of various cations and anions. Common cations include sodium, potassium, calcium, magnesium, barium, strontium and iron. Typical anions include chloride, sulfate, and carbonate species. The concentrations of these ions affect buffering capacity (alkalinity), scaling potential (precipitation) and salinity (Hansen and Davies 1994). The wide diversity of different ions correlates to an exponentially larger amount of various ionic complexes.

Total dissolved solids (TDS) measures the concentration of dissolved constituents in water and is generally used as an indicator for salinity. A low saline, coal bed methane PW could contain about 10,000 mg/l (part per million; ppm) of TDS, while the high range in the Marcellus could contain up to 400,000 ppm TDS (Harto and Veil 2011). TDS varies by well, formation and time (Kondash, Albright, and Vengosh 2017).

On average, PW ranges anywhere from 30,000 to 75,000 ppm TDS (Harto and Veil 2011). As PW TDS is often above that of seawater (about 35,000 ppm), it is generally classified as hypersaline.

Various heavy metals can exist in PW. These include cadmium, chromium, copper, lead, zinc, silver, and nickel (Hansen and Davies 1994). It is also possible that PW contains trace amounts of precious metals (such as platinum). Detection of minute concentrations and complex-harvesting methods of these precious metals from PW is an area of current research at Texas A&M Kingsville. In general, concentration of dissolved heavy metals depends on the formation and age of production (Utvik 2003).

PW has been found to contain naturally occurring radioactive materials (NORM). NORM in PW are commonly radium isotopes (^{226}Ra and ^{228}Ra) and are often co-precipitated with scales causing radioactive scaling issues (Fakhru'l-Razi et al. 2009, Stephenson 1992). The most common radioactive scale is barium sulfate. One study found radium and barium isotope levels in PW far above drinking water standards (13-3000 times the EPA's MCL) (Haluszczak, Rose, and Kump 2013).

2.3.2 Organics

In the E&P industry, the primary organics of concern are oil and natural gas hydrocarbons. HC include saturates, aromatics, asphaltenes and resins (Das and Chandran 2010). Examples include BTEX (benzene, toluene, ethylbenzene, xylene); PAH's (polycyclic aromatic hydrocarbons); and NDP (phenols, napthalene, phenantherene and dibenzothiophene) (Ekins, Vanner, and Firebrace 2007). While some

HC are slightly soluble, most are not. The result is a PW with some soluble but mainly dispersed oil (Fakhru'l-Razi et al. 2009).

Soluble organic compounds are polar. Generally, these compounds are in the low to medium carbon range (Fakhru'l-Razi et al. 2009). PW pH, temperature, salinity and formation pressure affect solubility (Das and Chandran 2010, Martins and Peixoto 2012). Soluble organics typically include formic acid, propionic acid, BTEX, phenols, aliphatic hydrocarbons, carboxylic acids and low molecular weight aromatic compounds (Fakhru'l-Razi et al. 2009, Stephenson 1992). The HCs with highest solubilities in PW are BTEX and phenols (Fakhru'l-Razi et al. 2009). In contrast to this solubility, BTEX has a high volatility – making gassing off a concern.

Free or dispersed oil in PW consists of coalesced, non-polar oil droplets that are insoluble (Fakhru'l-Razi et al. 2009). Typically, less soluble hydrocarbons in PW are PAHs and heavy alkylated phenols (Faksness, Grini, and Daling 2004). Dispersed oil will also include any soluble organics above the super-saturation concentration.

2.3.3 Injected chemicals

Produced water may contain chemicals used during completion as well as additives used for treatment, prevention and operational purposes. Biocides, corrosion inhibitors and oxygen scavengers are added as preventative measures. Friction reducers and gels are added to change the viscosity values of the water for lower pumping pressures, to clean the well of suspended particulates and to prevent stuck pipe. Wide ranges of chemicals are used such as anionic polysaccharides and various organic polymers (McCormack et al. 2001). The amount of chemicals needed and added varies by well.

2.3.4 Solids

PW can contain organic and inorganic solids. The former includes bacteria, asphaltenes and paraffin waxes. The latter includes suspended formation, corrosion and scale particles (Fakhru'l-Razi et al. 2009). Innate formation bacteria include sulfate-reducers (SRB), iron-reducers (IRB), acid-producers (APB), fermentative microbes, acetogens and methanogens (Li, Kang, and Zhang 2005). Hydrocarbon-degrading microorganisms may be present.

Among the possible PW bacteria, SRBs are arguably the most notorious in oil and gas. These microorganisms convert sulfate to sulfides, and the aqueous sulfide ions can equilibrate with air to produce hydrogen sulfide gas (H_2S). This is a major concern in E&P operations as H_2S is corrosive and lethal at high concentrations. Other common bacteria that can exist once the water has surfaced are aerobic microbes (Wang et al. 2001). Since PW is typically stored in large volumes prior to disposal, these storage tanks can serve as a feeding ground for bacteria, which is especially concerning if SRBs and sulfate are present. Saturated hydrocarbon, such as asphaltenes and waxes, can precipitate and form as solids in PW. Inorganic crystalline solids, such as silicon dioxide, ferrous and ferric oxides and barium sulfate, can also exist in suspension in PW (Deng et al. 2009). Presence of suspended particles is important to address as solids can lead to damage, such as formation plugging (Veil 2015).

2.3.5 pH

Another important PW quality parameter is pH. Harto and Veil used a version of the United States Geological Survey (USGS) PW database to evaluate pH distributions throughout various formations (Harto and Veil 2011). They found that most formations had an average neutral pH of 7.5. The high and low extremes were a pH of 5 and 9. The pH is very important as it affects solubility, precipitation, volatilization and bacterial growth, and is subject to change over time.

2.4 Treatment technologies

Recent advancements in E&P completion chemicals have significantly reduced the effect of salinity and TDS on completion make-up water (Boschee 2014). Consequently, PW treatment for reuse in E&P operations typically only requires suspended solids and oil removal. If PW were to be reused for domestic or irrigation purposes, a much higher level of treatment, such as desalination, would be required given the potential presence of toxic contaminants and hyper-salinity. Whether reusing in E&P operations or recycling in another industry, disinfection of the treated water is often required.

2.4.1 Suspended solids and oil removal

Gas flotation is the conventional suspended solids and oil separation technology used for produced water and is often used as a primary means of treatment (Igunnu and Chen 2012). This process involves aerating the water with bubbles. As the bubbles travel toward the surface of the water, oil and particles are flocculated and form a foam that is skimmed off of the water (Casaday 1993). There are two main types of gas flotation, induced gas (IGF) and dissolved gas flotation (DGF), which produce varying bubble sizes. Oil and grease, volatiles and suspended particles as small as 25 microns (μm) can be removed by gas flotation with no chemical use; a coagulant can improve this removal to 3 μm (Çakmakce, Kayaalp, and Koyuncu 2008, Casaday 1993, Hayes and Arthur 2004, Mines 2009).

A hydrocyclone is a treatment process that uses the difference in densities of water and solids to separate oil and suspended solids from water (Igunnu and Chen 2012). A hydrocyclone contains a circular top and conical body. Fluids flow into the top and spiral down through the conical body. The clean water flows back up through an outlet on the top while the contained sludge exists through the bottom of the funnel (Systems 2010). The performance of a hydrocyclone depends on the angle of the conical chamber and can remove particles as small as 5 to 15 μm (Ltd. 2010, Mines 2009).

Media filtration is often used for removal of dissolved and dispersed organics from PW. Conventional water treatment media, such as sand, gravel and anthracite, have been used. However, the most common and often most effective media in PW is walnut shell filters (Mines 2009). Removal efficiencies of oil and grease and total organic carbon (TOC) up to 90% have been reported. A main disadvantage has been regeneration or disposal of fouled media. However, certain companies have modified walnut shells to enable greater removal and regeneration ability.

High pore size membranes, such as microfiltration (MF) and ultrafiltration (UF), can remove oil and suspended particles. With a pore size ranging from 0.1 to 10 μm, MF is generally used as a pretreatment and for the reduction of suspended solids and turbidity (Igunnu and Chen 2012). With pore sizes ranging from 0.01 and 0.1 μm, UF membranes are one of the most effective technologies at removing oil from PW (He and Jiang 2008). Membranes are made from a wide range of materials, of which the most common are polymeric and ceramic. For PW, the latter is often favored over the former due to ceramic's high durability and resistance to temperature and chemicals. Cross-flow filtration is the most common method of operation. In cross-flow, the PW feed flows perpendicular to the membrane surface in order to minimize fouling and particle build up (Dickhout et al. 2017). Eventually, the feed water is too concentrated to continue treatment; leaving a treated effluent (permeate) and waste concentrate.

Evaporation ponds are used to either store or dispose of large volumes of PW. The primary disposal method is evaporation from solar energy; warm, dry climates are ideal (Velmurugan and Srithar 2008). These ponds allow particles to settle out and oil to float to the top of the water to be skimmed. The final fate of the water has typically been evaporation to the atmosphere. However, as the particles and oil separate out, evaporation ponds can be used as a suspended solids and oil treatment for PW.

2.4.2 Desalination

Low pore size membranes, nanofiltration (NF) and reverse-osmosis (RO), use osmotic pressure to diffuse water through a non-porous membrane and effectively remove dissolved ions. The smallest particle size that NF can typically remove is that of a divalent ion whereas an RO can remove most monovalent ions and larger. Contaminants as small as 0.1 nm can be removed by a seawater RO; however, membrane fouling is the primary disadvantage for RO systems, especially with an inconsistent feed like PW (Mines 2009, Wilf et al. 2007). NF and RO require substantial energy to overcome the osmotic pressure and can be costly compared to less intensive treatments. Like MF and UF, NF and RO are run in cross-flow filtration mode, producing a clean permeate and waste concentrate.

Thermal treatment technologies are also used to desalinate PW. The most common thermal technologies are multi-stage flash (MSF), vapor compression distillation (VCD) and multi-effect distillation (MED) (USBR 2003). The primary mechanism in each of these thermal processes is to evaporate the water and leave behind the salt. Often, the water is condensed to generate a product rather than evaporate directly to the atmosphere. The MSF process heats the influent water and exposes it to a lower pressure, causing flash evaporation of the water. In VCD, the vaporized water is compressed, either thermally or mechanically, to increase its temperature. This temperature is captured as an energy source and fed back to the vaporization unit. The MED process applies pressure and thermal energy to evaporate the water and subsequently condense it. The process is called an “effect”. Multiple effects are used to increase recovery efficiency of the treatment. MED and VCD hybrids have been used in order to increase water recovery and energy consumption efficiency (Igunnu and Chen 2012).

2.4.3 Disinfection

Chemical oxidation is typically used for disinfection of PW. Bacterial growth issues are a primary driver for disinfection. Color, odor, organics, inorganics and microbes can be oxidized depending on the amount of oxidant used. Chlorine, ozone, peroxide, permanganate and oxygen are oxidants that are typically used. Chlorine, in the form of chlorine dioxide (ClO_2), is the most common used in the oilfield due to low cost and ease of chemical generation on-site. Due to health concerns with ClO_2, ozone and peroxide are becoming more popular. If reusing water in E&P operations, common practice is to disinfect with an oxidant and maintain a residual biocide concentration to inhibit bacterial regrowth.

2.5 PW costs and regulations

2.5.1 Regulations

PW is considered an industrial waste or pollutant. As a pollutant, management and disposal must comply with federal and state regulations. There are 31 oil and gas producing states in the U.S. (Veil 2015). Each has its own regulatory framework. Federally, PW is regulated by the Clean Water Act. The US Environmental Protection Agency (USEPA) established effluent guidelines for oil and gas in 40 CFR Part 435 in 1979 (USEPA 2017). These regulations cover onshore and offshore oil and gas discharges occurring from all aspects of an E&P project, including PW. Per the most recent amendment, onshore PW cannot be directly discharged to the waters of the US without a permit nor can it be sent to a publicly owned treatment works (POTW).

Whether PW is injected or treated for re-use, it must meet the applicable standards set by the USEPA. For injection, the Underground Injection Control (UIC) program is the managing body. UIC established Class II injection wells primarily for oil and gas wastewater. Class II wells consist of disposal and enhanced oil recovery wells. The former is disposal only while the latter is used for enhancing HC production from wells. Enhanced recovery wells are the most common type of Class II well (McCurdy 2011, USEPA 2016). The EPA National Pollutant Discharge Elimination System (NPDES) handles point source pollution discharges. An NPDES permit must be obtained and discharge standards must be met prior to discharge or reuse of PW. Due to the potential presence of toxins, obtaining an NPDES permit for surface water discharge is near impossible.

Permitting for injection well operation and the number of Class II wells varies by state. For example, Pennsylvania has only 8 Class II wells in the state, compared to Texas' greater than 12,000 injection wells (McCurdy 2011). In the Oklahoma Arbuckle formation, seismicity has been linked to injection wells, and injection rate restrictions have shown a decline in earthquakes (Teague 2016). While the most common form of PW disposal is a Class II injection well, many companies fear that Class II wells may become more restricted.

2.5.2 Costs

Just as PW volume and constituents are highly varied, the specific water management costs are highly variable. The main cost components in the water management lifecycle are sourcing, storage, transportation, treatment and disposal (Slutz et al. 2012). Specific costs and estimating formulas are often kept confidential and difficult to obtain from companies. However, general costs for water management components can be found in literature or by personal communication with operating personnel. It is important to note that these costs are specific to the time of each publication. Most of these costs vary by region and are influenced by the position of the market. For example, if the oil price is high, service companies can charge more for water management cost. Nevertheless, a literature was conducted in order to understand various ranges of costs observed in the field.

2.5.2.1 Transportation

Transportation is one of the largest components in oil field water management and can either occur by trucking or pipeline (Eaton 2014). Conventionally, trucking has been the most common means of E&P water transportation. Trucking cost is primarily a factor of time. This includes the time it takes the truck to drive to the well and to the SWD, plus the time it takes to load and unload the PW – which can be significant in regions with high E&P activity. As this cost is a function of distance, truck volume and overall time, costs presented in literature vary with respect to units. Slutz et al. (2012) presented a general range of $0.02-0.04 per bbl per mile. Dunkel (2016) used $1.50 per bbl for 10 miles ($0.15 per bbl per mile). McCurdy (2011) estimates an average of $1.00 per bbl per hour. For areas with many SWDs like Texas, this translates to $0.50-1.00 per bbl. On the contrary, in areas with few SWDs like Pennsylvania, this could mean $4.00-8.00 per bbl for trucking (McCurdy 2011). Wolfcamp Water Partners reported $1.50 per bbl minimum or greater than $0.09 per bbl per mile (Partners 2011). In the Permian and Eagle Ford basins, trucking costs range from $70-110 per hour (Cook, Huber, and Webber 2015, Eaton 2014).

Potential cost savings and social benefits for water pipeline infrastructure has become a significant topic in recent publications (Collins 2016, Dunkel 2016, Jacobs 2016, Schilling 2016). Primary social benefits of pipelines include reducing traffic, road damage and exhaust pollution from trucks in areas with high oil and gas activity. Pipelines range from temporary (lay-flat, fast line or lock-ring irrigation pipe) to permanent, such as high-density polyethylene (HDPE) or metal pipe (Dunkel 2016, Slutz et al. 2012). As material and construction costs vary significantly, pipeline costs range considerably and are reported as a simple dollar per bbl per mile. Slutz et al. (2012) reports a range of $0.02-0.40 per bbl per mile, ranging from lowest fast line to highest HDPE pipe cost. Dunkel (2016) reports $3-4 million for a 12 inch, buried HDPE pipe with 35,000 bbl per day capacity spanning 10 miles and operating at $0.03 per bbl. Assuming full capacity operating at a year, this equates to an overall estimate $0.03 per bbl per mile. Wolfcamp Water Partners has a pipeline cost of less than $0.02 per bbl per mile (Partners 2011). Collins (2016) states a lay flat pipeline range of $0.02-0.03 per bbl per mile for two pipe vendors in the Eagle Ford and Permian basin.

2.5.2.2 Disposal

Recall from Section 2.5.1, Class II injection wells are the most common form of disposal of PW. SWDs are a subset of Class II wells used primarily for disposal. The cost of injection is variable by the regional geology, which influences the capacity and cost to drill the SWD. (Slutz et al. 2012) documents a range of injection costs of $0.75-3.00 per bbl. In addition to regional geology, supply-and-demand also affects injection cost. In regions where SWDs are numerous, like the Barnett or Eagle Ford, lower injection costs occur. In areas where SWDs are scarce or non-existent, like the Marcellus, Arbuckle, and parts of the Bakken, costs are much higher. Formation plugging and capacity issues also affect the overall injection cost (Slutz et al. 2012). Cook, Huber, and Webber (2015) observed Permian and Eagle Ford injection costs from $0.60 to several dollars per bbl. McCurdy (2011) reported commercial SWD disposal costs of $0.50-2.50 per bbl. Injection costs in the Bakken were estimated to be between $0.50 and $1.75 per bbl (Center 2010, Ruyle 2015).

2.5.2.3 Treatment

The treatment cost is widely varied and dependent upon many different factors, including constituents in the water, desired effluent criteria, power source availability and treatment technology used. As this treatment cost is set by the company providing the service, the ultimate cost per bbl will be a factor of treatment unit capital, operation and maintenance, profit margin and personnel required. Depending on the amount of supervision, personnel alone could cost $1.00 per bbl or more (Dunkel 2016). For water requiring minimal treatment, such as suspended solids and oil removal, the treatment cost could range from $1.00-2.00 per bbl. For extensive treatment and cleaner effluent, such as desalination, treatment cost could range from $3.50-6.25 per bbl (Slutz et al. 2012). In 2016, Approach Resources reported an overall cost of $1.50 per bbl at one of their PW treatment systems, while Apache reported a cost of only $0.29 per bbl (Collins 2016). The specific treatment goals of each plant are not known; however, it is important to note the high variability in treatment costs.

2.5.2.4 Source water

Source water cost for E&P operations is variable depending on type of water (i.e. ground water, surface water, treated PW, municipal effluent) and drought conditions of the region. Slutz et al. (2012) observed surface water costs as low as $0.01-0.02 per bbl in the Marcellus. Ground and surface water ranged from $0.25-0.35 per bbl in the Barnett, Eagle Ford and Haynesville. In the Bakken and Denver-Julesburg, source water ranged from $0.50-1.00 per bbl (Slutz et al. 2012). Sharr (2014) reports fresh water sourcing costs ranging from $0.30-0.80 per bbl in the Eagle Ford. Arnett et al. (2014) proposed an average cost of $0.50 per bbl for ground water in the Eagle Ford. In the Permian, ground water prices range from $0.16-0.50 per bbl, with an average and extreme of $0.37 and $0.80 per bbl (Cook, Huber, and Webber 2015). Collins (2016) reported Permian fresh water costs in the range of $0.40-0.50 per bbl, Santa Rosa brackish water as $0.35-45 per bbl and Odessa municipal effluent as $0.27 per bbl.

2.6 PW management and treatment models

Slutz et al. (2012) developed an economic model for flowback water management in shales. This paper laid the groundwork for the research presented in this thesis. The primary economic criteria in a shale water management plan were identified as cost and availability of source water, transportation, disposal and treatment. The paper identified these aspects as key building blocks for an economic model. Reuse and recycle definitions are separate in this model. The former applying to minimal treatment for reuse in E&P operators; the latter implying substantial treatment such that recycle into the environment or other beneficial use is possible. The model is intended for flowback management, thus considers short-term treatment and reuse of flowback water. It does not consider long-term management strategies for PW.

AQWATEC at Colorado School of Mines, in partnership with Kennedy/Jenks Consultants and Argonne National Laboratory, developed a model called the Produced Water Treatment and Beneficial Use Screening Tool. The aim of this particular tool was to facilitate beneficial reuse of produced water and assist in treatment and management decision making (AQWATEC 2016). The model is Excel spreadsheet based and consists of four modules: water quality, treatment selection, beneficial use screening and beneficial use economic modules. The model study area consists of five coal bed methane basins in the Rocky Mountains. The water quality module contains water quality and quantity data from these basins to enable the user to either predict or input PW characteristics. The treatment selection module assists the user in selecting a treatment configuration that can produce effluent quality required for a given beneficial use. The beneficial use screening module screens through potential forms of beneficial uses that may be applicable given the input. The beneficial use economic module evaluates capital and operating expenditures of obtaining beneficial use in order to provide the user with the relative economic feasibility based on inputs (AQWATEC 2016).

PacWest Consulting Partners developed an economic model upon being approached by an E&P client seeking to further understand water treatment and reuse possibilities in the Eagle Ford shale (Robart 2012). This model was built to understand long-term lifecycle water management and models sourcing, transportation, storage, pumping (hydraulic fracturing), treatment and disposal costs. It uses dynamic variables to adjust for changes in field conditions and evaluates multiple water treatment options. The model evaluates options for 5 and 20 year lifespans, discounting cash flows for both, and includes drilling schedule uncertainty and variability. In Robart (2012), three scenarios were presented for the client operator. All were assuming a large field of 1,367 wells drilled in five years. One scenario used sourcing fresh water and injection disposal, and the other two assumed treatment and reuse. Results indicated significant cost savings for treatment and reuse; however, no input data was provided in the paper thus making it difficult to corroborate the results.

Gao and You (2015) developed a model to optimize shale gas water management by minimizing the overall cost and use of water. The model was formulated as a mixed-integer linear fractional programming (MILFP) problem and was solved using three different algorithms, including parametric, reformulation-linearization and an algorithm that combines the branch-and-bound and Charnes-Cooper transformation method. The formulated model simulates injection disposal, centralized water treatment and on-site treatment. All aspects are modeled for each, including mass balance, cost, capacity, composition, bounding and logic constraints. Input parameters include treatment type, recovery, capacity and cost for various TDS levels; water sourcing type, cost, demand and production; gas production and revenue per well; capital and operating expenses of various transportation methods; operating cost and capacity of injection wells. The overall model has 297 discrete variables and iterates through using the methods above to optimize the MILFP problem and produce the most optimized combination of disposal or treatment (Gao and You 2015).

Lira-Barragán et al. (2016) developed a model that addresses uncertainty in shale water management and synthesizes water networks. The uncertainties include fracturing volume requirements and flowback production. The aim of the model is to optimize flowback management and minimize the amount of fresh water consumed and risk of ground water contamination during treated water discharge. The model produces probability curves for costs and water demand and calculates treatment, storage and disposal capacities. The goal is to assist decision makers with properly sizing water systems and provide insights into worst and best case scenarios with probability curves (Lira-Barragán et al. 2016).

3. MODEL THEORY

3.1 Key assumptions

The model developed in this research is based on the input perspective of an operator, the company that is managing the development and production of a well or lease. The user inputs cost, water production and distance information for a field. The model uses this information to simulate multiple scenarios for that particular field. As operators manage the development, understanding the economics from the primary decision maker's perspective benefits both the operator and the service company. The operator can use this model to understand the total cost and risk for various water management strategies. The service company can use this model to understand how a specific treatment technology fits into an operator's budget and can simulate the various field conditions that would warrant a technology economically viable.

The model assumes no existing infrastructure. This assumption primarily relates to storage and pipeline costs. The purpose of this assumption is to provide a planning tool for a company to layout a new project. Fields with existing infrastructure can still be modeled by inputting no cost for the appropriate variable.

3.2 Treatment inputs

In several of the published models and PW research, a specific type of treatment technology is modeled or evaluated. When observing treatment from a macroscopic viewpoint, submersing into much detail regarding treatment specifics is unnecessary. The primary benefit of treating PW is recovering a percentage of the original water that has value. This value, either in revenue or source water savings, translates to a reduction in the overall water management cost. If the treatment cost is low enough and the water value is high enough, the net water management cost could be lower than the overall injection cost. It is important to note this relationship between treatment cost and product water value. For example, a higher and broader contaminant removal treatment will result in a higher cost, but this increase in removal produces a cleaner effluent with a higher value. Rather than induce error by attempting to model actual treatment processes, this model recognizes that the market determines both the treatment cost and the effluent water value.

This model will look at two broad treatment classifications: conventional and zero liquid discharge (ZLD). Conventional treatment refers to a treatment technology that produces a treated water for revenue/savings and wastewater for disposal. The relative amounts of treated water and wastewater depend on the recovery (%) of the treatment system. The recovery is the percentage of clean water extractable from an initial volume of PW. Conventional treatment can be modeled by two inputs from an operator's perspective: cost per barrel and percentage recovery. The cost per bbl is charged by the service company and is a factor of the service company's capital expenses (CAPEX), operational expenses (OPEX), labor and maintenance; the treatment recovery is determined by the treatment technology and system design. Both of these variables are entirely independent of the operator. Section 3.4.3 explains the formulas developed for mobile and centralized conventional treatment.

ZLD treatment technology produces a solid waste rather than a liquid. This often occurs through flash evaporation of the water. The vapor can either be condensed or entirely vented to the atmosphere. Given high TDS levels of PW, the solid precipitates generated in this process are mostly salt. As some companies claim this salt has potential value, a ZLD system has two recovery terms – one for water and one for salt. Section 3.4.4 explains the formulas developed for mobile and centralized ZLD systems.

3.3 Primary costs

The model utilizes input information to output the total and net water management costs for various management approaches. In Equation 1, the total water management cost is comprised of storage, transportation, treatment and disposal costs (Slutz et al. 2012). The net water management cost is the difference between the total water management cost and the amount of savings or revenue generated by the recovered water from treatment (Equation 2). As the objective of the model is to evaluate and compare water management strategies, only these costs are considered. It should be noted that these costs are internal costs within the total cost of a well. It is assumed that the non-water management related costs are the same for each scenario.

$$C_{Total}=C_{Storage}+C_{Transporation}+C_{Treatment}+C_{Disposal} \quad 1$$

$$C_{Net}=C_{Total}-S_{RecoveredWater} \quad 2$$

3.4 Formula development

3.4.1 Volume

3.4.1.1 Annual average input

The constant average input is an annual input of barrels per year. This value is specific to each well and is used per year dependent upon the project lifetime input. $V_{i,x}$ is the annual water production for well i in year x (Equation 3). The total water produced per well i is simply the sum of the annual water production from the first year, x, to the project lifespan, Y. The total water produced in the field, V_{Tot}, is the sum in bbl of total the water produced from wells i to n, where n is the total number of wells (Equation 4).

$$V_{i,x}=V_{ave_{i,x}} \qquad 3$$

$$V_{Tot}=\sum_{i=1}^{n}\sum_{x=1}^{Y}V_{i,x} \qquad 4$$

3.4.1.2 Decline curve

While the water cut of a well (% water to total liquids) often increases throughout its lifetime, the actual water production often declines over the lifetime of the well. Assuming a constant average could overestimate the amount of water produced per well. Water production can be input using a decline curve. Arps (1945) first applied decline curves to estimate recovery from conventional wells. Since then, decline curves have been used to estimate oil, gas and water production (Arps 1945, Bai, Goodwin, and

Carlson 2013, Ilk et al. , Jackson et al. 2014, Kondash, Albright, and Vengosh 2017, Mutalik and Joshi 1992, Valko and Lee 2010, Wang and Zhang 2014). Past water production data can be used to estimate input parameters in the decline curve equations by conducting a decline curve analysis and forecasting the production curve. The model input uses input parameters to generate a curve that is integrated to calculate yearly volumes. The input, *qi*, is the initial water production rate in barrels per year. If no decline curve is used, the initial rate is equal to the annual average. The initial decline, *Di*, and decline coefficient, *b*, determine the amount of decline and shape of the curve. When *b* is 0, the equation is exponential and Equation 5 is used. Equation 6 is used when *b* is greater than 0. When *b* is between 1 and 0, the curve is hyperbolic. When *b* is equal to 1, the curve is harmonic. Existing production data should be used to calculate these parameters. *Vi,x* is the annual production (bbl/year) of well *i* in year *x*. The total water produced per well *i* is the sum of *Vi,x* over all years *x* to the project lifetime *Y*. The total volume for the field is still Equation 4 and is the sum of the total water produced per well *i* summed over all wells from *i* to *n*.

$$V_{i,x}=\int_{x-1}^{x} q_i e^{-D_i t}\,dx \qquad 5$$

$$V_{i,x}=\int_{x-1}^{x} \frac{q_i}{(1+bD_i t)^{\frac{1}{b}}}\,dx \qquad 6$$

3.4.2 Salt water disposal (SWD) well injection – baseline

Salt water disposal (SWD) well injection is the most common and often most economical form of PW management (McCurdy 2011). The model uses SWD injection as the baseline for evaluating treatment and reuse. The total and net SWD disposal costs are the same as the entire volume of water is disposed of and there is no product water for savings or sale. The total SWD cost is equal to the sum of storage, transportation and injection cost and is depicted in Equation 7.

$$C_{SWD}=C_{storage,SWD}+C_{trans,SWD}+C_{disposal,SWD} \qquad 7$$

The first term of Equation 7 is the storage cost and is a function of the number of tanks per well *i* ($N_{PW,i}$), cost per tank ($c_{tank,i}$) and the number of wells (n) (See Equation 8). As this is an initial capital cost, it is not a function of time as are the transportation and disposal costs. The number of tanks varies per well and is dependent upon the amount of water produced, the size of tank used and the frequency in pickup. However, these specific details were not included in the first iteration of the model and only the number of tanks is input by the user. It is shown later in Section 4.2 that this initial investment in storage is often insignificant in the total cost.

$$C_{storage,SWD}=\sum_{i=1}^{n}\left(N_{PW,i}*c_{tank,i}\right) \qquad 8$$

Transportation and disposal costs are depicted in Equations 10, 11 and 12. Trucking is the primary form of transportation from well to SWD and is a function travel time ($t_{d\text{-}SWD}$), load/unload time (t_L and t_U), cost per hour (c_{truck}), truck volume (V_{truck}) and total volume per well *i*. Equation 9 is used to calculate the number of trucks (n_{trucks}) required per well *i* in year *x*. The travel time can be estimated by multiplying the distance by two and dividing by the average truck speed (Equation 10). This is assuming the truck is traveling from the SWD to the well and back. With addition of Google Maps API, a database that can be queried to determine the distance and time between geographic locations, an accurate travel time is calculated between the well location and SWD location (input as latitude and longitude) (Equation 11). Injection cost is merely a function of cost per barrel (c_{inj}) and total disposed volume over the lifespan of (Equation 12). Both transportation and disposal are also a function of project lifespan.

$$n_{trucks_{i,x}}=\mathrm{roundup}\left(\frac{V_{i,x}}{V_{truck}}\right) \qquad 9$$

$$C_{trans,SWD}=c_{truck}*\sum_{i=1}^{n}\sum_{x=1}^{Y}\left(\left(2*\frac{d_{w\text{-}SWD,i}}{S_{ave}}+t_L+t_U\right)*n_{trucks_{i,x}}\right) \qquad 10$$

$$C_{trans,SWD}=c_{truck}*\sum_{i=1}^{n}\sum_{x=1}^{Y}\left(\left(2*t_{d_{w\text{-}SWD},i}+t_L+t_U\right)*n_{trucks_{i,x}}\right) \qquad 11$$

$$C_{disposal,SWD}=c_{inj}*V_{tot} \quad 12$$

3.4.3 Conventional treatment

3.4.3.1 Mobile (on-site) treatment

The total and net water management costs for mobile (on-site) treatment follow the same general formula as in Equations 1 and 2. The storage equation (Equation 13) includes an additional tank input for the treated water ($N_{TW,M}$); it is assumed that the effluent is stored in the produced water tank. If the treated water can be sold or reused on or near the location, the main advantage of mobile treatment is reducing the amount of water that needs to be transported (Equation 14). The reduction factor is 1-R_m, where R_m is the mobile treatment recovery in percent. If the water needs to be transported to a location for sale or reuse, an additional term must be added to the transportation equation. In Equation 15, it is assumed that all of the water is treated, where $c_{trmt,M}$ is the specific cost of mobile treatment in dollars per bbl. Another advantage of treatment is reducing the amount of waste needing disposal as seen in Equation 16. It is assumed that the water is either resold at source water value (c_{SW}) or reused, saving a source water expense (Equation 17).

$$C_{storage,M}=\sum_{i=1}^{n}((N_{PW,i}+N_{TW,M_i})*c_{tank,i}) \quad 13$$

$$C_{trans,M}=c_{truck}*\sum_{i=1}^{n}\sum_{x=1}^{Y}\left(\left(2*t_{d_{w-SWD},i}+t_L+t_U\right)*(1-R_M)*n_{trucks_{i,x}}\right)_x \quad 14$$

$$C_{treatment,M}=c_{trmt,M}*V_{tot} \quad 15$$

$$C_{disposal,M}=c_{inj}*(1-R_M)*V_{tot} \quad 16$$

$$S_{RW,M}=c_{sw}*R_M*V_{tot} \quad 17$$

3.4.3.2 Centralized treatment

The total and net water management costs for centralized treatment follow the same general formula as in Equations 1 and 2. The storage cost includes produced water tanks on each well, wastewater tanks at the centralized facility ($N_{WW,C}$) and treated water tanks ($N_{TW,C}$) at the centralized facility (Equation 18).

$$C_{storage,C}=\sum_{i=1}^{n}((N_{PW,i}+N_{TW,C}+N_{WW,C})*c_{tank,i}) \quad 18$$

The model considers both trucking (Equation 19 and 20) and pipeline (Equation 21) as transportation for a centralized facility, where $t_{dw-c,i}$ is the travel time from well i to the centralized facility. If the centralized treatment is not located at the SWD, an additional term, $C_{trans,C\text{-}SWD}$, is needed to calculate the cost of transportation from the centralized to the SWD for either trucking or pipeline (Equations 22 and 23).

$$n_{trucks,c\text{-}swd}=\text{roundup}\left((1\text{-}R_C)*\frac{V_{tot}}{V_{truck}}\right) \qquad 19$$

$$C_{trans,C_T}=c_{truck}*\sum_{i=1}^{n}\sum_{x=1}^{Y}\left(\left(2*t_{d_{w\text{-}c},i}+t_L+t_U\right)*n_{trucks_{i,x}}\right)_x+C_{trans,C\text{-}SWD_T} \qquad 20$$

$$C_{trans,C_P}=c_{pipe}*\sum_{i=1}^{n}\left(t_{d_{w\text{-}c},i}*V_i\right)+C_{trans,C\text{-}SWD_P} \qquad 21$$

$$C_{trans,C\text{-}SWD_T}=c_{truck}*\left(2*t_{d_{c\text{-}SWD},i}+t_L+t_U\right)*n_{trucks,C\text{-}SWD} \qquad 22$$

$$C_{trans,C\text{-}SWD_P}=c_{pipe}*(1\text{-}R_C)*V_{Tot} \qquad 23$$

The treatment formula is the same as mobile; however, the cost per barrel for centralized treatment, $c_{trmt,C}$, is considered an independent input as this price may be different from a mobile unit (Equation 24). Due to economies of scale, higher volumes may result in lower costs for treatment systems; however, it is beyond the scope of this model to determine the actual treatment cost. Disposal cost and source water revenue or savings are modeled the same as in mobile yet with a recovery input for the centralized treatment system, R_C (Equations 25 and 26).

$$C_{treatment,C}=c_{trmt,C}*V_{tot} \quad 24$$

$$C_{disposal,C}=c_{inj}*(1-R_C)*V_{tot} \quad 25$$

$$S_{RW,C}=c_{sw}*R_C*V_{tot} \quad 26$$

3.4.4 Solid waste treatment systems (Zero liquid discharge)

Recall that the model considers ZLD treatment in addition to conventional treatment. The primary assumption in zero liquid discharge (ZLD) is that the entire water feed is evaporated, leaving a solid waste that must be disposed. The evaporated water is either condensed to recover the water or evaporated into the atmosphere. The cost formulas are based on GPRI pilot plant experience with ZLD technologies.

The total (Equation 27) and net (Equation 28) ZLD equations are similar to the general equations in the conventional treatment section in that they include storage, transportation, disposal, treatment and savings/revenue terms. Instead of liquid waste disposal, the ZLD equation includes a solid waste disposal term. Transportation includes both solids to a landfill and liquid to the centralized plant – depending on mobile or centralized ZLD. The ZLD net equation contains two savings/revenue terms, one for product water ($S_{RecoveredWater}$) and one for salt ($S_{RecoveredSalt}$). Some companies promote that precipitated salt could be sold for industrial manufacturing or road salt application. It should be noted that toxins and impurities might precipitate along with the salts; quality assurance and quality control precautions should be considered if this is to be considered in a treatment design.

$$C_{Total,ZLD}=C_{Storage,ZLD}+C_{Transporation,ZLD}+C_{Treatment,ZLD}+C_{Disposal,Solids} \quad 27$$

$$C_{Net}=C_{Total}-S_{RecoveredWater}-S_{RecoveredSalt} \quad 28$$

3.4.4.1 Mobile (on-site) ZLD

In order to compare with conventional treatment, mobile and centralized ZLD approaches are considered. The mobile approach assumes a ZLD unit on each pad. Storage includes tanks for PW and for the input feed of the ZLD (N_{ZLD}) (Equation 29). The latter is an option and not as necessary as the former since the unit could draw feed directly from the PW tank battery. The treatment cost, $c_{ZLD,M}$, is in dollars per bbl as used in conventional treatment (Equation 30).

Recall that it is assumed that the water is completely evaporated, precipitating the suspended and dissolved contents of the water. This assumption is utilized in Equation 31 to estimate the weight of solid product in tons, $W_{i,x}$, from the water for each well i in each year x. TSS and TDS are measurements in mg/l, or parts per million (ppm), of the amount of suspended and dissolved material in the water. A conversion factor is used, $\Upsilon_{ppm\text{-}ton/bbl}$, to convert ppm to ton per bbl. In Equation 31, it is assumed that the entire amount of mass observed in these measurements precipitates. Two errors in estimated weight can occur in this formula: solids loss to atmosphere in the emission and water adsorption to the precipitated solids. In application of this equation, it is assumed that these errors are negligible. This is not correct in the field; however, it allows for an estimation of solids production based on minimal input. The solids disposal is calculated as a dollar per ton, c_{solids}, summed over each of the wells i for each year x (Equation 32). The recovery term, R_{solids}, represents the fraction of salts that are valuable and can be recovered and sold.

The trucking equation is similar to the trucking equations used in the previous sections (Equation 33 and 34). Instead of a trucking liquid volume input, it is a truckload capacity, L_{truck}, input in tons. The number of trucks is equal to the amount of solids of which must be disposed divided by the load capacity of truck (Equation 33). This is rounded up to the nearest integer. Typically, maximum load capacity is 20 tons per truck. The amount of savings or revenue is equal to the amount of water recovered from the ZLD treatment multiplied by the cost of source water (Equation 35). The recovery coefficient, R_{ZLD}, in Equation 35 is a percentage of the amount of evaporated water that is condensed. Therefore, the percentage of water not recovered, equal to 1-R_{ZLD}, is assumed to be lost to the atmosphere. If capture is not part of the ZLD process, the recovery term is zero. Equation 36 is used to calculate the revenue generated from selling valuable salt product precipitated during the ZLD process, where c_{salt} is the value for which product salt could be sold. It is assumed that the product salt is sold locally does not include shipping costs.

$$C_{Storage,ZLD_M}=c_{tank}*\sum_{i=1}^{n}\left(N_{PW,i}+N_{ZLD,i}\right) \qquad 29$$

$$C_{Treatment,ZLD_M}=c_{ZLD,M}*V_{Tot} \qquad 30$$

$$W_{i,x}=\gamma_{ppm-\frac{ton}{bbl}}*\left(X_{TSS,i}+X_{TDS,i}\right)*V_{i,x} \qquad 31$$

$$C_{Disposal,Solids}=(1-R_{solids})*\sum_{i=1}^{n}\sum_{x=1}^{Y}\left(W_{i,x}*c_{Solids}\right) \qquad 32$$

$$n_{trucks,ZLD_{i,x_M}}=roundup\left(\frac{(1-R_{solids})*W_{i,x}}{L_{truck}}\right) \qquad 33$$

$$C_{trans,solids}=c_{truck}*\sum_{i=1}^{n}\sum_{x=1}^{Y}\left(\left(t_{d_{W-LF,\,i}}+t_{L,ZLD}+t_{U,ZLD}\right)*n_{trucks,solids_{i,x}}\right)_x \qquad 34$$

$$S_{RW,ZLD_M}=c_{sw}*R_{ZLD,M}*V_{Tot} \qquad 35$$

$$S_{salts,ZLD}=R_{solids}*c_{salt}*\sum_{x=1}^{Y}\sum_{i=1}^{n}\left(W_{i,x}\right)_x \qquad 36$$

3.4.4.2 Centralized ZLD

In a centralized ZLD treatment scenario, the storage equation includes the number of PW tanks on each well and the number of storage tanks at the centralized plant ($N_{ZLD,C}$) (Equation 37). Equation 38 is similar to Equation 30 for treatment; however, the treatment cost per barrel for centralized ZLD, $c_{ZLD,C}$, is independent from mobile ZLD. The transportation equations (Equations 39 and 40) for centralized ZLD are similar to that of conventional treatment equations since the first transportation is of liquid from the well to the centralized facility. The difference is the solids transportation cost from the centralized facility to a landfill or solids disposal facility. Equation 41 and 42 are used to calculate the total weight of solids in all waters from each of the wells *i* and the number of trucks in year *x* required to haul that waste. Equation 43 is used to calculate the cost to truck these solids from the centralized plant to the landfill or solids disposal facility. Equation 44 is the same as Equation 35 includes the ZLD water recovery, $R_{ZLD,C}$, for centralized rather than mobile. The excess percentage of water, 1-$R_{ZLD,C}$, is assumed to be lost to the atmosphere. The solids revenue from centralized ZLD is also calculated using Equation 36.

$$C_{Storage,ZLD_C}=C_{tank}*\left(\sum_{i=1}^{n}\left(N_{PW,i}\right)+N_{ZLD,C}\right) \qquad 37$$

$$C_{Treatment,ZLD_C}=c_{ZLD,C}*V_{Tot} \qquad 38$$

$$C_{trans,ZLD_{C,T}}=c_{truck}*\sum_{i=1}^{n}\sum_{x=1}^{Y}\left(\left(2*t_{d_{w-c},i}+t_L+t_U\right)*n_{trucks_{i,x}}\right)+C_{trans,C-LF_T} \qquad 39$$

$$C_{trans,ZLD_{C,P}}=c_{pipe}*\sum_{i=1}^{n}\left(t_{d_{w-c},i}*V_i\right)+C_{trans,C-LF} \qquad 40$$

$$W_x=\gamma_{ppm-\frac{ton}{bbl}}*\sum_{i=1}^{n}\left(\left(X_{TSS,i}+X_{TDS,i}\right)*V_{i,x}\right) \qquad 41$$

$$n_{trucks,ZLD_x}=roundup\left(\frac{(1-R_{solids})*W_x}{L_{truck}}\right) \qquad 42$$

$$C_{trans,C-LF}=c_{truck}*\sum_{x=1}^{Y}\left(\left(t_{d_{C-LF}}+t_{L,ZLD}+t_{U,ZLD}\right)*n_{trucks,ZLD_x}\right) \qquad 43$$

$$S_{RW,ZLD_C}=c_{sw}*R_{ZLD,C}*V_{Tot} \qquad 44$$

3.4.4.3 ZLD for concentrate handling of other treatment systems

A ZLD system could be used for handling the waste stream of other treatment systems, such as reverse osmosis. In which case, calculations are included in the model for this possibility in order to determine the most optimal placement of treatment. The $C_{Disposal}$ term in the mobile and centralized conventional treatment equations are replaced with ZLD equations. This induces an additional treatment cost per bbl for ZLD and solids disposal cost instead of SWD injection. An additional savings/revenue term for water is input into the net equation in case the ZLD produces a condensed product water stream. Also, the salt product (Equation 36) is included in the net water management equation..

3.5 Breakeven costs

The feasibility of treatment and reuse can be evaluated by using a breakeven treatment cost metric. An operator breakeven treatment cost (OBE) is defined as the explicit cost of treatment ($/bbl) that makes the net treatment and reuse equation equal to the total SWD injection equation. A service company breakeven treatment cost (SCBE) is defined as the lowest treatment cost that a service company can charge an operator. If the SCBE is less than or equal to the OBE, treatment and reuse is feasible because the service company can make money and the operator can save money by treating and reusing as opposed to SWD injection. If the SCBE is greater than the OBE, treatment and reuse is not economically feasible. In such case, the economics are not justified and other factors, such as environmental consideration, droughts or regulations, must outweigh the economics in order for treatment and reuse to occur. Such factors are beyond the scope of this model and are not considered. The benefit of the OBE is making treatment cost an output rather than an input for a particular scenario. For example, if the OBE is $2 per bbl for particular field conditions, service companies now understand that any price above $2 per bbl is not competitive against SWD injection.

3.6 Application

The model outputs have applications that extend beyond one specific type of company. The total and net water management costs are most applicable to an operator company seeking to plan a field. An actual field site can be input into a virtual space. The model can then be used to simulate a variety of what-if scenarios on the field and allows operators to quantify the risk of a specific water management strategy.

The breakeven treatment costs, OBE and SCBE, benefit a service company or water treatment company that desires to understand more about the overall PW management economics, as seen in the example at the end of Section 3.5. The tool provides these companies with the ability to understand the field conditions that make their treatment technology competitive with SWD injection.

3.7 Disclaimer

It should be noted that the equations previously developed in this model are accurate to the best knowledge of the author at the time of this publication. Algorithms were developed to represent the most significant cost variables within produced water management. The specific inputs into the model are highly variable and may change significantly if the price of oil changes. For example, the current oil price is near $50 per bbl. Operators are focusing on minimizing operating expenses to maximize margins. For the given oil price, an SWD may only be able to charge $60 per hour. However, if the price of oil returns to $120 per bbl, the same company may potentially increase their target cost to $90 per hour. Therefore, the cost inputs in this model are dependent upon the market. While inputs may change, the model formulation and framework developed in this model will not change.

4. MODEL EVALUATION

4.1 Background

A model is a virtual representation of reality. This model is a combination of mathematical formulas that is used to simulate real world costs. In any transcription of reality to virtual space, errors and risks are inherent and expected (Loucks et al. 2005). The main sources of errors are in the model inputs and calculations. If it is assumed that the calculations are correct, the primary source of error can be attributed to the model input parameters. In the upstream oil and gas industry, field conditions are constantly changing well-to-well, field-to-field, play-to-play, region-to-region. Therefore, the uncertainty that induces error is the lack of accurate input information due to changing field conditions, and risk is the possible impact of making decisions based on this uncertainty (Mao-Jones 2012).

Two analyses are commonly used to evaluate risk and error – sensitivity and uncertainty analyses. The former seeks to determine the output variance based on the change of a specific input variable. The latter is used to evaluate the probability or risk of all potential changes in variables in order to quantify the probability of possible results. The sensitivity analysis was used in this project to determine the primary economic drivers – the variables with the greatest impact on the economic output. The uncertainty analysis was used to determine the probability for each of the outputs, based on all possible input conditions. The results from both analyses provide information that is assessed and used to draw conclusions that support the research objectives.

4.2 Sensitivity analysis

The aim of the sensitivity analysis is to evaluate the discrete impact that changes in each variable has on the outputs. To accomplish this, each variable is assigned a base value that is used in each iteration. The value is varied from its specified minimum to maximum and the effect on the output is recorded. The range of values was selected to capture a reasonable range that could be seen in the field. Table 4.1 depicts the values used. It should be noted that these values do not depict the exact minimum and maximum extremes but are based on values found in the literature review (Section 2.5) and actual experience. The simulation is repeated for each of the specified variables. The change in each output is recorded and is used to evaluate the significance of the variables. TopRank by Palisade, an Excel add-in software, and the spreadsheet-based model was used to conduct this analysis.

Results are displayed using tornado graphs, which display the range of the specific output for each variable's minimum and maximum value. The variables are displayed in order of impact; those with the highest impact on the output are displayed at the top of the graph. Tabular data for each of the tornado graphs is contained in Appendix A.

Table 4.1 Sensitivity analysis base, minimum and maximum values.

Input	Unit	Base	Minimum	Maximum
Cost per tank	*$/tank*	10,000	5,000	15,000
Treatment cost	*$/bbl*	2.5	2	3
Recovery	*%*	70	55	85
Source water cost	*$/bbl*	1.5	1	2
Injection cost	*$/bbl*	0.9	0.3	1.5
Pipeline cost	*$/bbl/mile*	0.07	0.04	0.1
Number of wells	*wells*	50	25	75
Average volume	*bbl/well/year*	30,000	15,000	45,000
Average distance	*miles*	30	5	75
Lifespan	*years*	3	1	5
Trucking cost	*$/hour*	60	50	70
Average speed	*mph*	40	30	50
Load time	*hr*	0.5	0.25	0.75
Unload time	*hr*	0.5	0.25	0.75
Truck load	*bbl*	120	100	130

4.2.1 SWD injection

The primary economic driver in the SWD injection cost output is the well-to-SWD distance (See Figure 4.1). This underscores the importance of transportation in PW management. The distance value was changed from 5 to 75 miles; therefore, the change was significant. As the distance in areas like Pennsylvania can be upwards of 200 miles, this range of extreme values is realistic. Injection cost is the second most significant variable. This input ranged from $0.30 to $1.60 per barrel. It is interesting to note that, while the distance was the most significant variable, the trucking cost components (cost per hour, truck speed, load/unload time, truck volume) had less of an effect. This validates the assumption of reducing the trucking equation down to a dollar per barrel per mile ($/bbl/mile) cost that was often found in literature (See Section 2.5.2). For the baseline distance and minimum and maximum trucking cost values, a per bbl per mile range of 0.02 to 0.07 can be estimated.

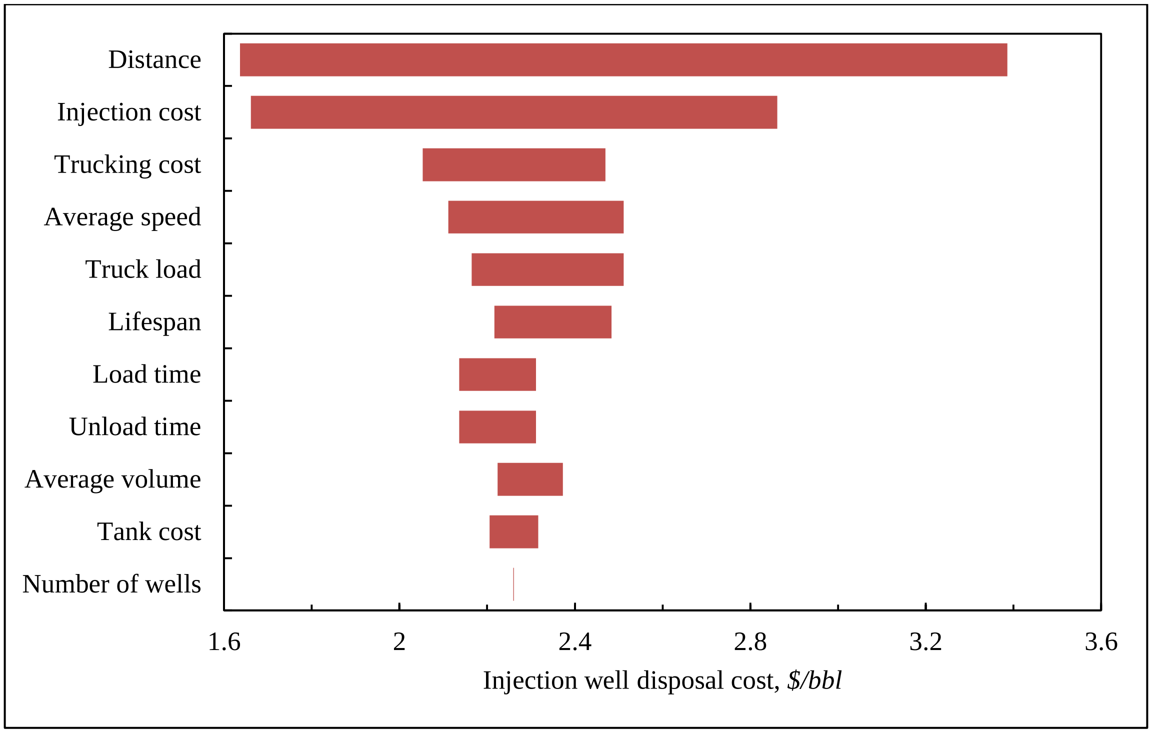

Figure 4.1 Tornado chart for injection well disposal output.

4.2.2 Mobile treatment

Treatment characteristics (cost per barrel and recovery) are the most significant variables for the mobile treatment and reuse scenario (See Figure 4.2). If the treated water can be reused or sold on-site, the primary advantage of using mobile treatment is reducing the amount of water that must be transported to the SWD. The more water that can be recovered at the lowest treatment cost per bbl, the more economical mobile treatment becomes. This is corroborated by recovery and treatment cost as the primary economic drivers. The third most important input is the source water cost. This is significant in the amount of savings/revenue that can be generated from treatment.

In Figure 4.2, it is seen that a higher lifespan has less of an effect at reducing the cost than a low lifespan has on increasing the cost. This is due to the law of diminishing returns as the initial storage capital is diluted out over longer lifespans. The well-to-SWD distance is not as critical in mobile treatment due to the reduction of volume that requires transport.

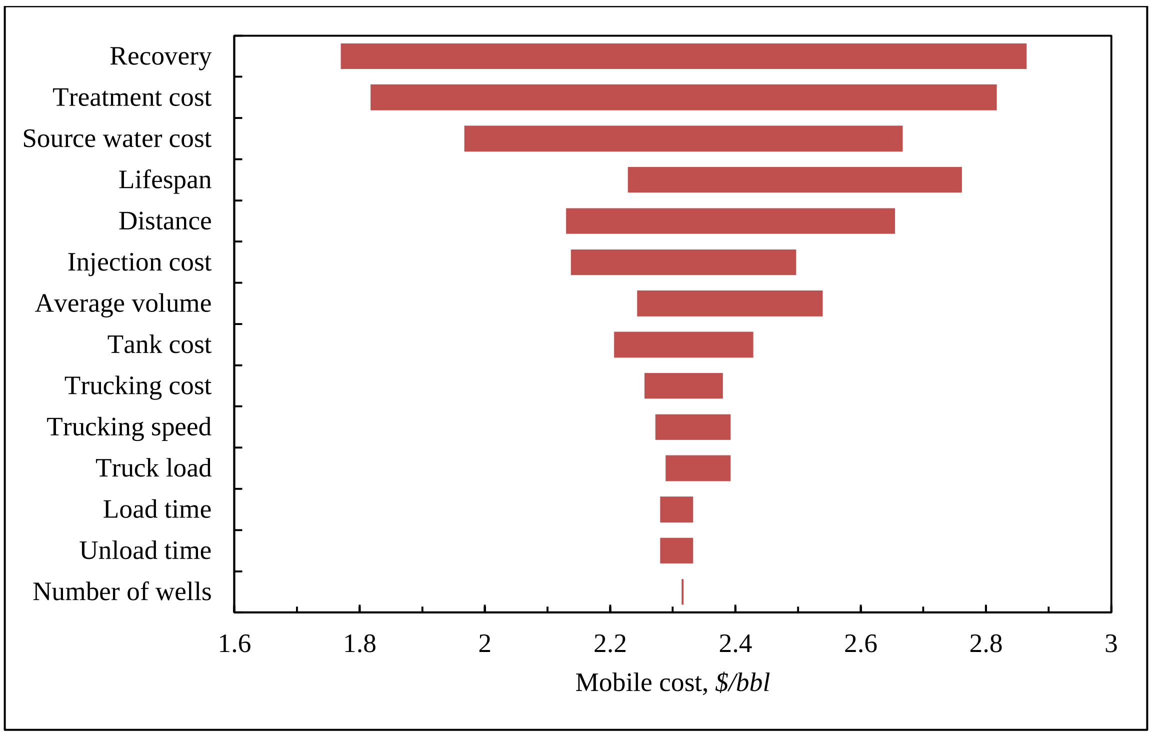

Figure 4.2 Tornado chart for mobile treatment output.

4.2.3 Centralized treatment

Both trucking and pipeline transportation methods were evaluated in the sensitivity analysis. Figure 4.3 shows centralized treatment with trucking, and Figure 4.4 shows centralized treatment with pipeline. In the trucking scenario, the well to centralized distance is the primary economic driver. This parallels the SWD injection scenario and is the result of the entire volume needing transport from the well to the centralized or SWD site. Treatment and recovery are the next most significant variables as these affect the amount and cost of water that can be reused or sold. Recall from Section 4.2.1, that the trucking cost inputs are less significant than the actual distance.

In centralized with pipeline, lifespan is the primary economic driver. A pipeline cost is an initial CAPEX. As the project lifespan increases, the CAPEX is diluted and becomes less significant. This effect is subject to the law of diminishing returns as seen in the skewness of the lifespan bar in Figure 4.4. A lifespan of five years resulted in a 13% reduction from the base value of $2.57 per barrel, but a lifespan of one year resulted in a 66% increase in cost. The well to centralized distance is the second economic driver. The reason is the same as seen in the centralized with trucking – the entire volume must be transported from the well to the centralized site. Treatment cost, recovery and source water cost are the next most significant variables as these influence the amount and value of product water. The pipeline cost did not have a radical effect due to the base lifespan of three years. However, it should be noted that very short project lifespans, high pipeline costs and long distances will make this variable more significant.

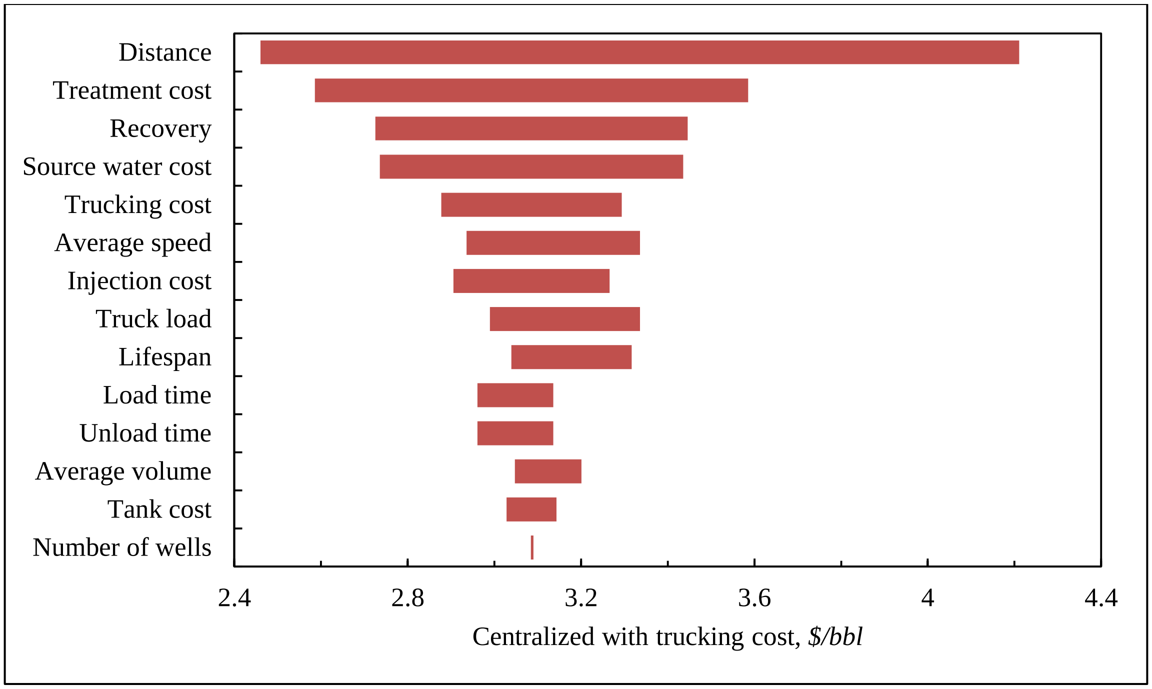

Figure 4.3 Tornado chart for centralized with trucking output.

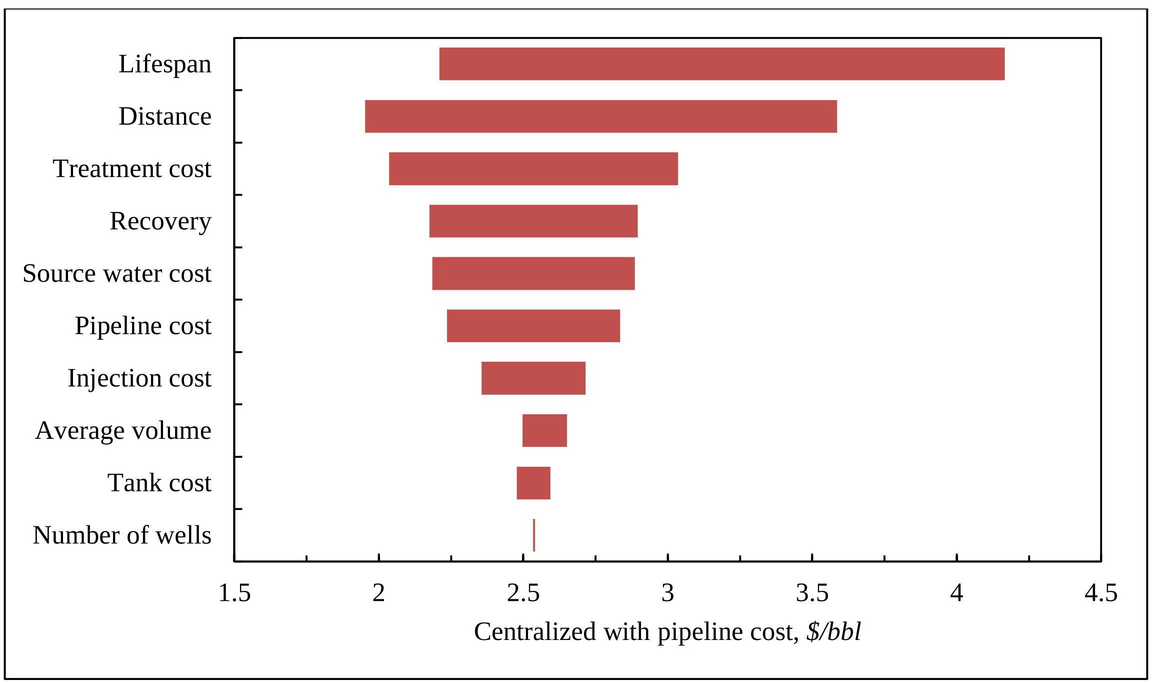

Figure 4.4 Tornado chart for centralized with pipeline output.

4.2.4 Mobile breakeven

Recall the operator breakeven cost (OBE) is the discrete cost of treatment for which the net treatment and reuse cost is equal to the SWD injection cost. A service company's treatment cost must be less than or equal to the OBE. Therefore, a higher OBE results in an increase in treatment and reuse economic feasibility. Figure 4.5 is the result for the mobile operator breakeven cost output (OBEM).

Distance is the primary economic driver because it is the most significant in determining the cost of SWD injection (See Section 4.2.1). At large distances, SWD injection is more expensive, and treatment is more feasible. The advantage of mobile is waste and transportation reduction. The recovery value is used to portray how much water is recovered and how much waste must be transported. Recovery is the second most significant variable. Injection cost is the third most significant variable as this affects the SWD injection total cost. Source water cost is also significant as this determines the value of the treated water.

It is illustrated in Figure 4.5 that long distances, high treatment recoveries, high injection and source water costs are the field conditions that increase the economics of mobile treatment and reuse. Specific trucking costs, volume, tank costs and the number of wells have little effect on the economics.

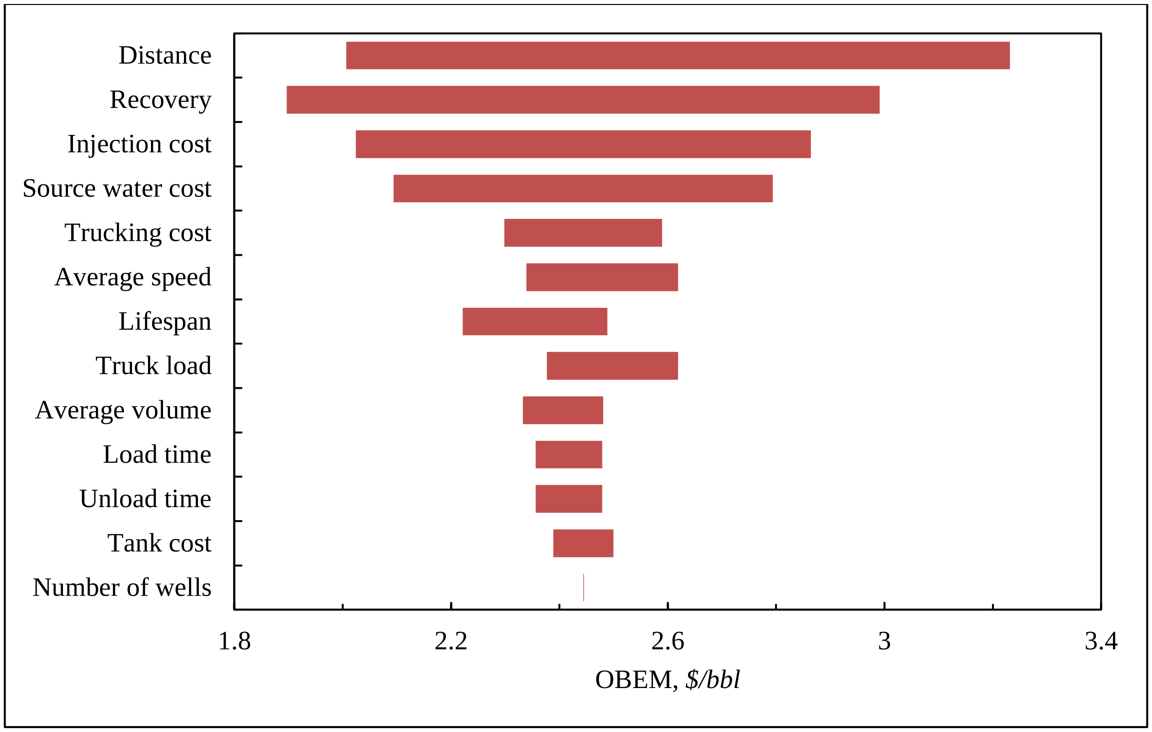

Figure 4.5 Tornado chart for operator mobile breakeven treatment cost (OBEM) output.

4.2.5 Centralized breakeven

The results for centralized with trucking operator breakeven treatment cost ($OBEC_T$) is displayed in Figure 4.6. Injection cost, recovery and source water cost are the most significant variables for $OBEC_T$. Higher injection costs make SWD more expensive. Higher recoveries and source water costs increase the value of treating water and improve overall treatment and reuse economics.

Lifespan is the primary economic driver in the operator breakeven treatment cost for centralized with pipeline ($OBEC_P$) (See Figure 4.7). A shorter lifespan results in a reduction in the economics whereas a longer lifespan results in an increase in the economics. As seen in both previous OBE's, injection cost, recovery and source water cost are significant. The final economic driver is pipeline cost.

Centralized with trucking treatment and reuse is economically feasible at high treatment recoveries, high injection and source water costs. Centralized with pipeline treatment and reuse is economically feasible at longer lifespans, high treatment recoveries, high injection and source water costs and low pipeline capital costs.

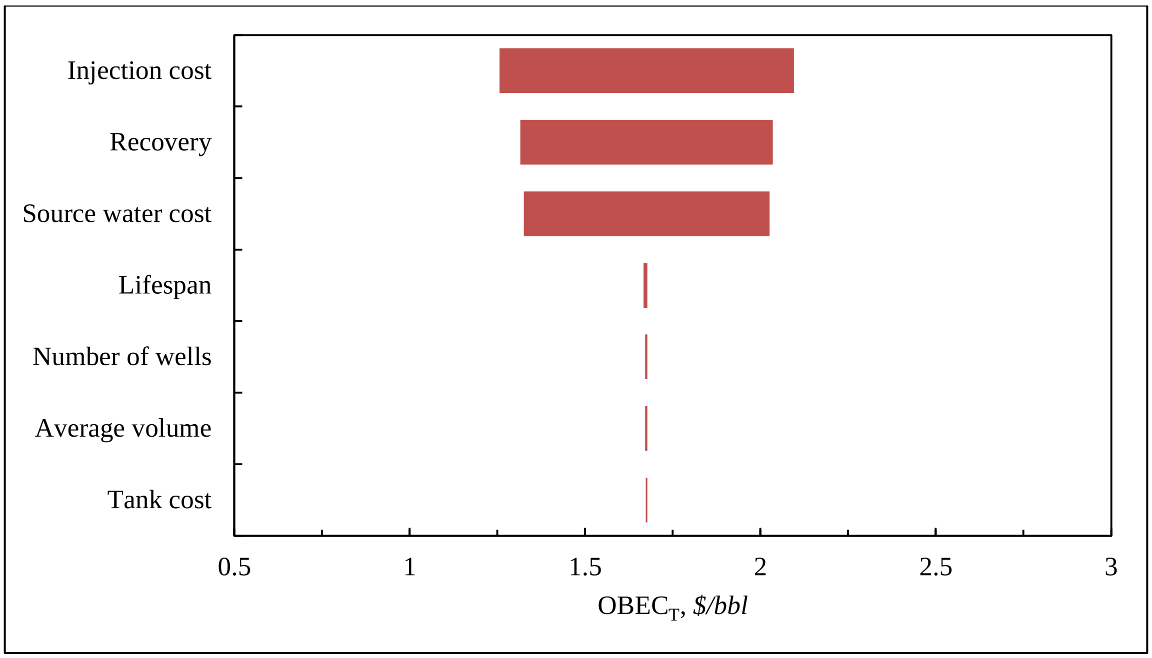

Figure 4.6 Tornado chart for operator centralized with trucking breakeven treatment cost ($OBEC_T$) output.

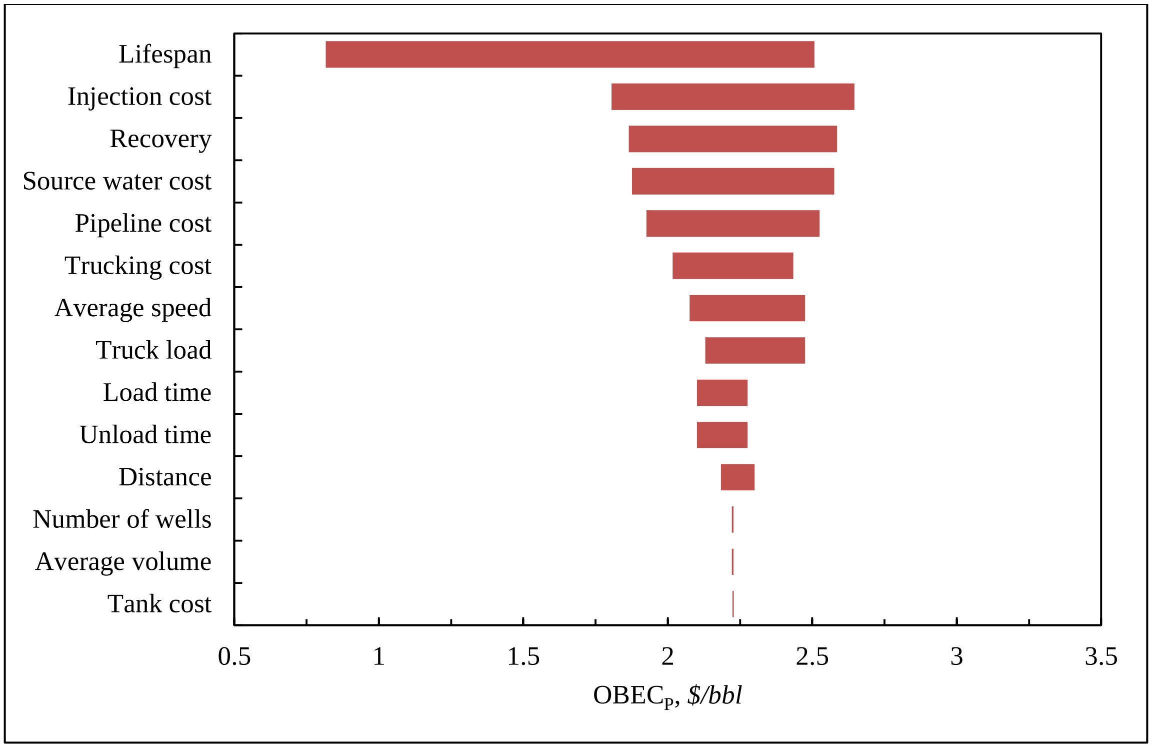

Figure 4.7 Tornado chart for operator centralized with pipeline breakeven treatment cost ($OBEC_P$) output.

4.2.6 Centralized-to-mobile ratio

In order to evaluate the relative economics, an OBE ratio of centralized to mobile (OBEC/OBEM) can be output and evaluated. When this ratio is greater than one, the centralized OBE is greater than the mobile OBE, and centralized is economically preferred. When the ratio is less than one, mobile is preferred. Understanding the sensitivity of this ratio provides insight into how mobile and centralized compare. Per Figure 4.8, under none of the input conditions is the $OBEC_T$/OBEM ratio greater than one. Therefore, for the input conditions, mobile is always more economical than centralized with trucking.

Centralized with pipeline is more competitive with mobile treatment and reuse (Figure 4.9). Lifespan is the primary economic driver, and shorter project lifespans shift the economics towards mobile. Distance is another main economic driver. At low distances, centralized is more economic. At high distances, the ratio is less than one, and mobile is preferred. Mobile treatment recovery has a larger effect than the centralized treatment recovery. The third most significant variable is pipeline cost. Low pipeline costs makes centralize with pipeline more economic. At low mobile recoveries, centralized with pipeline is more economical. At high mobile recoveries, mobile is preferred. Trucking cost inputs, water volumes, tank costs, injection costs, source water cost and number of wells have minimal effect on the relative economics.

For the input variables, mobile is always more economical than centralized with trucking. The conditions that promote centralized with pipeline over mobile are low distances, low lifespans, low recoveries and low pipeline costs.

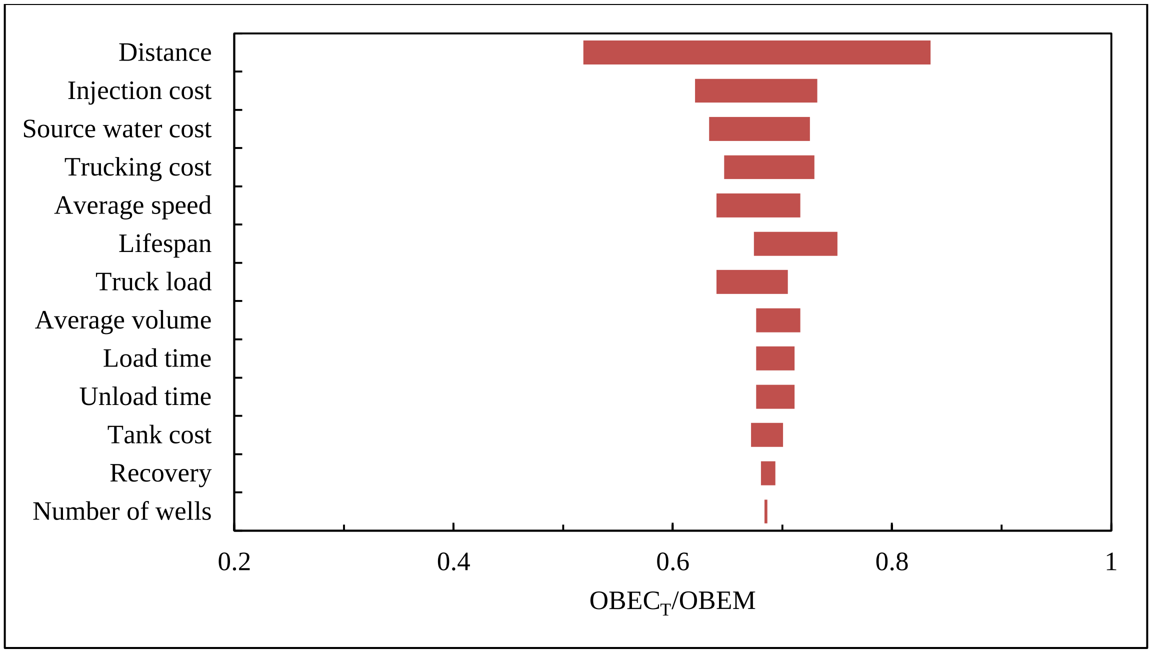

Figure 4.8 Tornado chart for $OBEC_T$/OBEM ratio output.

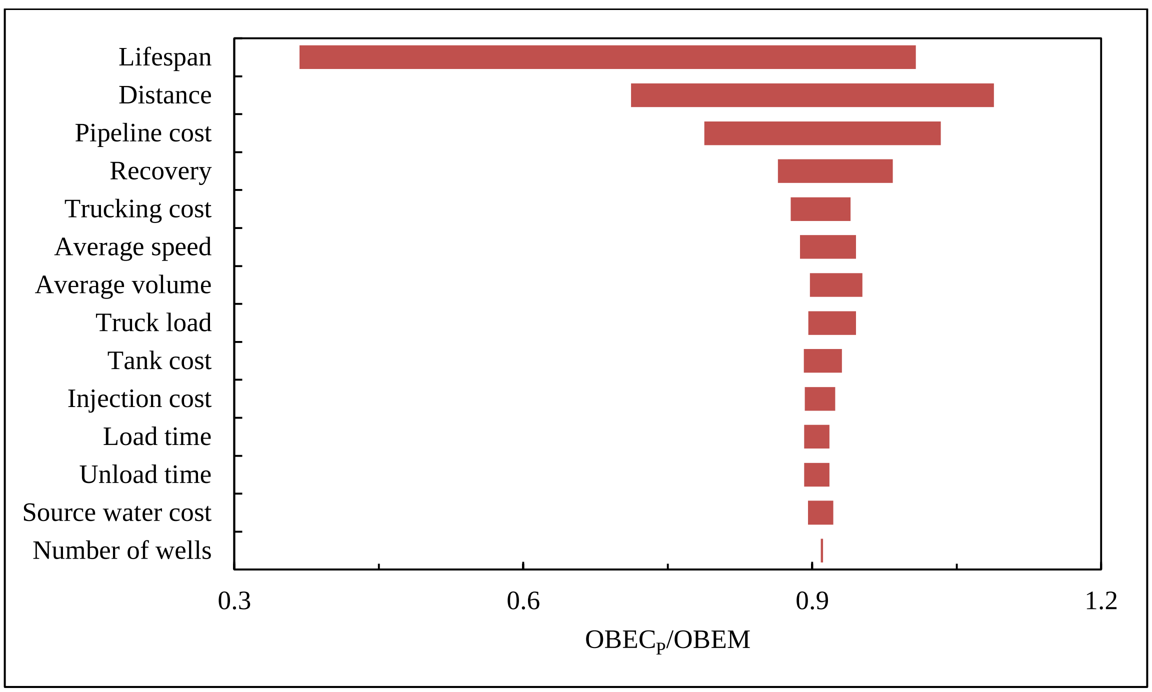

Figure 4.9 Tornado chart for $OBEC_P$/OBEM ratio output.

4.2.7 Zero liquid discharge treatment

Both a mobile and centralized approach to ZLD are evaluated; the minimum, maximum and base values used for the sensitivity analysis are displayed in Table 4.2. The inputs used for the ZLD sensitivity analysis are based on experience and industry input. As ZLD systems are energy intensive, the cost can be dramatic compared to conventional treatment. However, some companies claim that by harvesting flue gas for energy generation this cost could reach nearly a dollar per barrel. Therefore, a wide range of cost inputs from $1.00 per bbl to $9.00 per bbl are used. As not all ZLD systems condensate water, the recovery value is varied from 0 to 100% to simulate a system that vents all of the vapor as opposed to one that condenses all of it. Clark and Veil (2009) reported PW TSS concentrations up to 1,000 ppm, and TDS up to 400,000 ppm. The input ranges for both of these values were selected based on these values and experience. While recovering valuable salt from PW has many challenges due to the potential toxins in the water, it was modeled from 0 to 100% in order observe ideal and worst case scenarios. The solids disposal cost range is from industry input from an environmental engineering firm specializing in soil remediation. Road salt has been reported to range from $20-30 per ton to $100-180 per ton depending on the type of salt (Balakrishnan 2015). Therefore, a range of $35-150 per ton was used.

Table 4.2 Sensitivity analysis base, minimum and maximum values for ZLD.

Input	Unit	Base	Minimum	Maximum
ZLD treatment cost	*$/bbl*	5	1	9
ZLD recovery	*%*	50	0	100
Valuable salt recovery	*%*	25	0	100
Total suspended solids (TSS)	*ppm*	500	0	1,000
Total dissolved solids (TDS)	*ppm*	50,000	15,000	350,000
Solids disposal cost	*$/ton*	50	20	100
Load time	*hr*	0.5	0.25	0.6
Unload time	*hr*	0.5	0.25	0.6
Average speed	*mph*	40	30	50
Trucking cost	*$/hr*	60	50	70
Average well to landfill (W-LF) distance	*miles*	30	5	75
Salt resale value	*$/ton*	100	35	150

Per Figure 4.10**,** the primary economic driver for mobile ZLD is the cost of treatment. The wide range of inputs significantly affects the output cost. The second driver is the ZLD recovery value. This value represents the percentage of water that is captured after the ZLD process. If this recovery is zero, all of the original water is evaporated into the atmosphere. If this value is one hundred percent, all of the water is condensed for reuse. The more water recovered, the lower the overall cost is. The third significant variable is the recovery of valuable salt. This represents the percentage of the precipitate that may be sold for profit, as it is unlikely that all of the solid waste is valuable. TDS is the amount of dissolved material within the water. The higher the TDS, the more solid waste produced and higher overall cost per bbl.

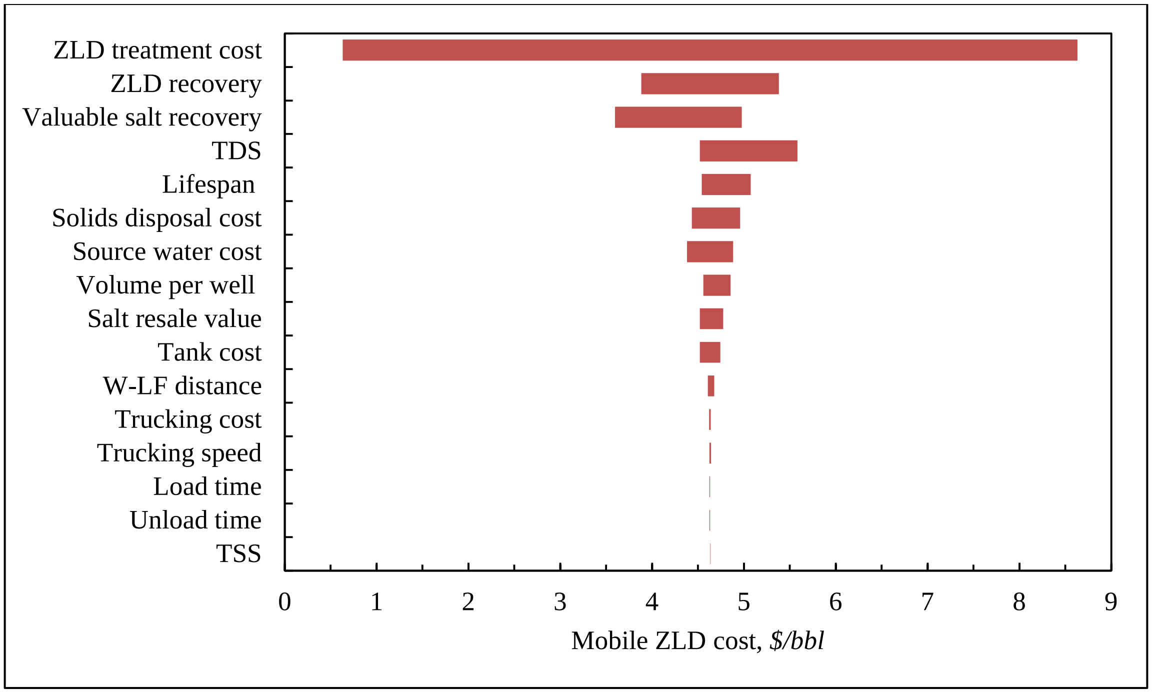

Figure 4.10 Tornado chart for mobile ZLD treatment and reuse.

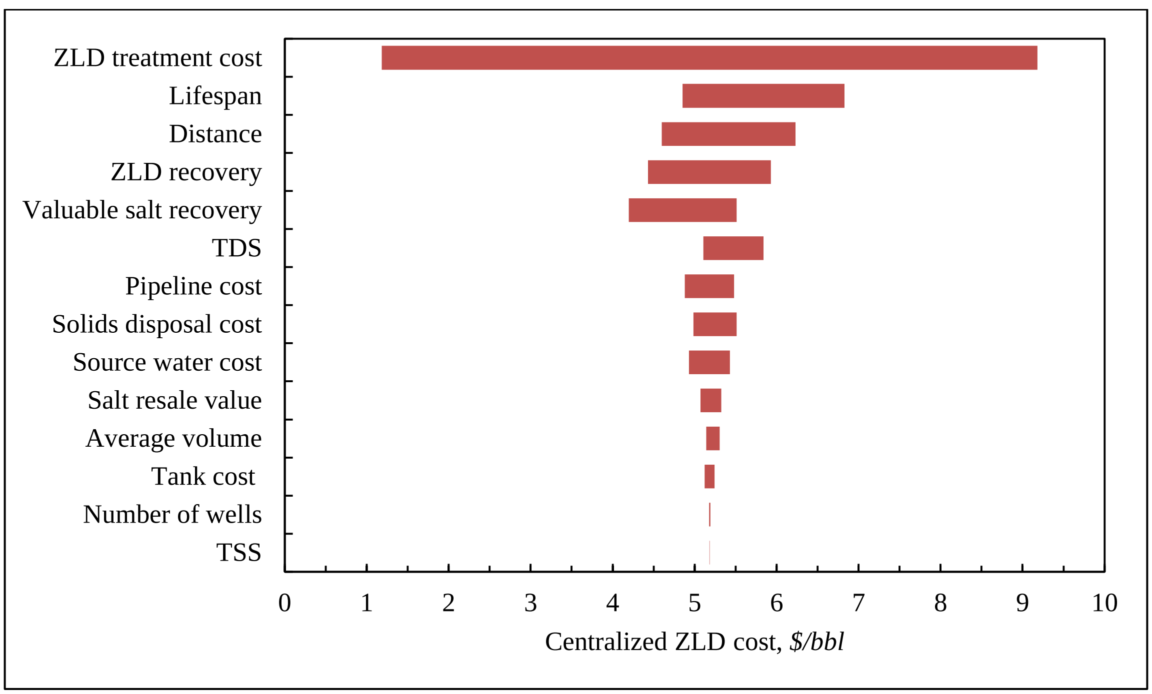

Figure 4.11 Tornado chart for centralized ZLD treatment and reuse.

As observed with mobile ZLD, the primary economic driver for centralized ZLD is also the cost of treatment (See Figure 4.11). As pipeline was seen to be more economical than trucking in the previous sections, this was used as the form of transportation for centralized ZLD. The lifespan is the second most significant variable as the longer the lifespan, the less intensive the initial CAPEX of a pipeline is. The well-to-centralized distance is a significant variable as all of the water must be transported to the centralized facility until volume reduction occurs. This is a disadvantage of centralized as shown previously (Section 4.2.3). ZLD recovery and recovery of valuable salts are also significant variables as these determine the amount of savings or revenue can be generated.

4.2.8 Zero liquid discharge breakeven

Recall that the operator breakeven cost is the discrete cost of treatment that makes the net treatment and reuse cost equal to the total SWD disposal. In Figure 4.12, the mobile ZLD operator breakeven treatment cost (OBEZM) ranges from near $1.50 per barrel to greater than $3.50 per barrel. A ZLD system that must charge greater than $3.50 per barrel is not economic for any of the conditions used in this sensitivity analysis. For energy intensive systems, measures should be taken to reduce the overall cost of treatment in order to make it economical.

The primary economic driver in mobile ZLD systems is the well-to-SWD distance. The greater the average distance, the more economical treatment is. Another important driver is the ZLD mobile recovery. This is the percentage of water captured for product. This is an important variable as one of the primary advantages of treatment and reuse is offsetting the overall cost by savings or revenue. A ZLD system with no capture will have to charge near $1.80 per barrel in order to remain economical for these base conditions. This low cost may be very difficult to achieve for most ZLD systems. The recovery of valuable salt, or percentage of precipitate that can be sold, is another important parameter as this revenue can be used to offset that overall cost. The injection cost is also important as this is used to determine the cost of SWD disposal. A high TDS lowers the OBEZM; an increase in TDS results in more solid waste for disposal. Even though a portion of this salt could potentially be sold, the increase in amount of valuable salt is outweighed by the increase in amount of waste salt in this case.

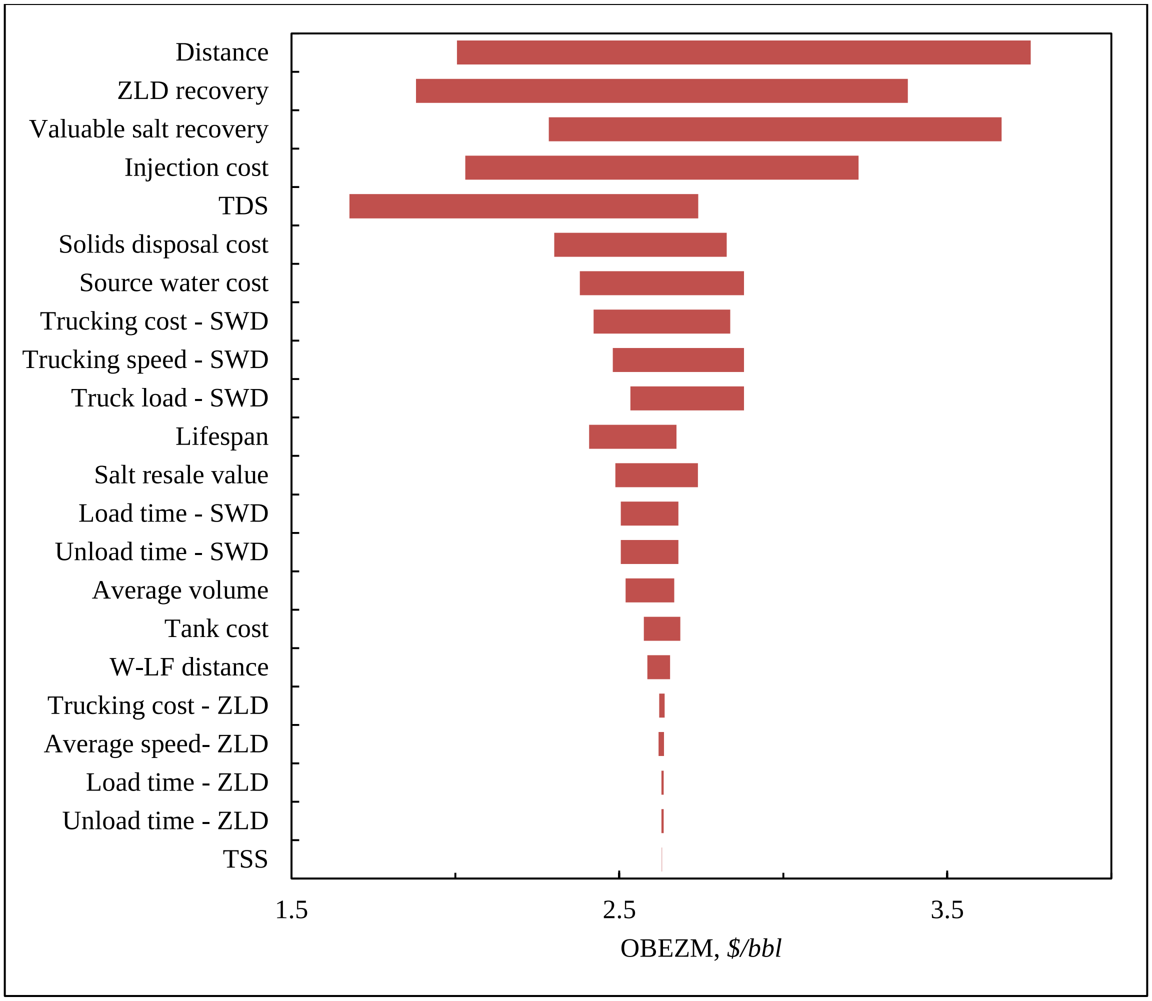

Figure 4.12 Tornado chart for mobile ZLD breakeven cost (OBEZM).

For the baseline conditions, a centralized approach with ZLD treatment is less economic than a mobile one. Per Figure 4.13, the overall operator breakeven cost for ZLD centralized (OBEZC) is generally lower than as was observed in Figure 4.12. It should be noted that pipeline is used as the means of transportation since this has been shown to be more economic than trucking in Sections 4.2.5 and 4.2.6. Lifespan is the most significant variable due to the initial CAPEX of the pipeline. ZLD recovery and valuable salt recovery are also significant as seen previously. Note that solids disposal cost is not significant even given the wide input range. The amount of solids produced is more important than the actual cost.

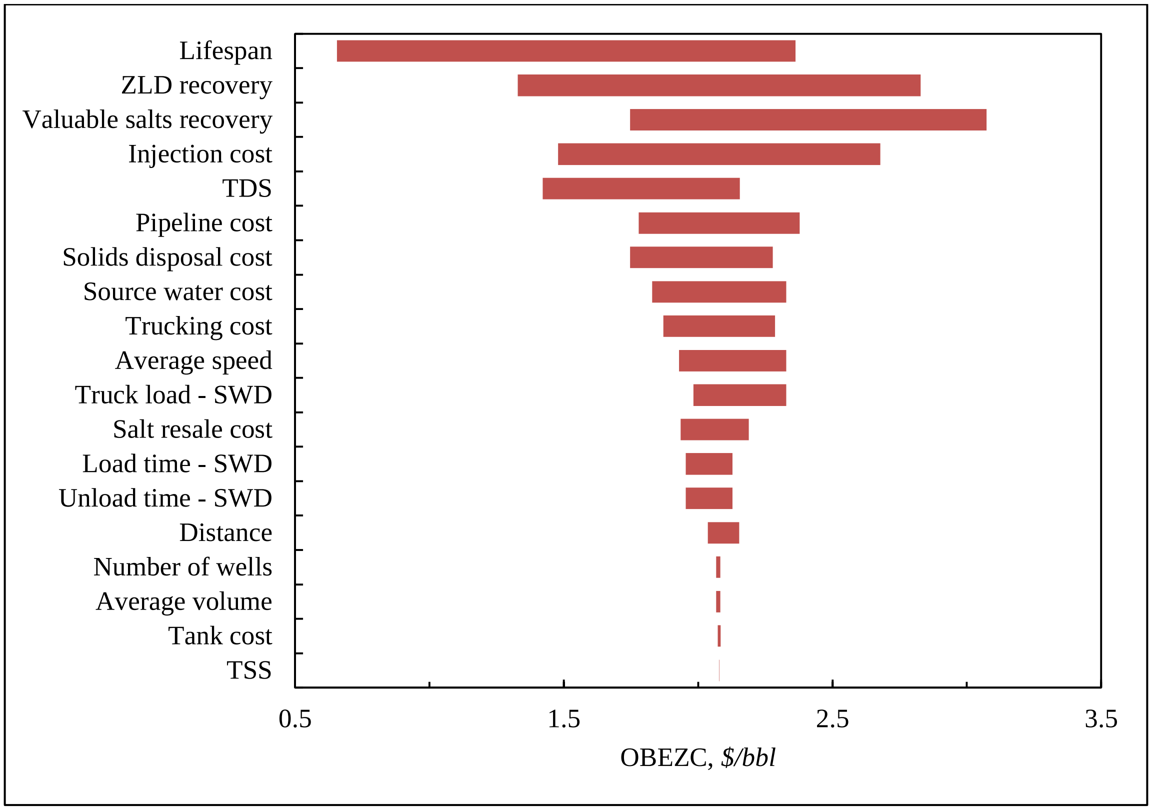

Figure 4.13 Tornado chart for centralized ZLD breakeven cost ($OBEZC_P$).

4.2.9 ZLD-to-conventional treatment ratio

The following Figure 4.14 and Figure 4.15 depict a similar ratio as seen in Section 4.2.6. The ratio in the previous section, centralized-to-mobile, was used to evaluate the relative economics between mobile and centralized liquid waste treatment. In this section, ZLD to conventional treatment ratios are evaluated for both mobile

(OBEZM/OBEM) and centralized with pipeline strategies ($OBEZC_P/OBEC_P$). This analysis is used to visualize how competitive a ZLD approach is compared to a conventional liquid waste treatment.

The primary economic drivers in the OBEZM/OBEM ratio are ZLD mobile recovery, recovery of valuable salts and mobile treatment recovery. A ZLD system with no water recovery or no salt recovery is not competitive with a conventional mobile treatment system. A high TDS equates to high solids and makes ZLD less competitive than conventional treatment. The volume of solids produced is more significant than the actual cost of solids disposal. Under the baseline conditions, mobile ZLD treatment is slightly more economic than conventional mobile treatment.

Under the base conditions, centralized ZLD with pipeline is slightly less economic than conventional centralized treatment. The primary factors are ZLD recovery and valuable salt recovery (See Figure 4.15). A high value for both of these recoveries yields ZLD more economic than conventional treatment. Although salt recovery is an advantage, a high TDS at the baseline of valuable salt recovery of 25% results a significant shift toward conventional treatment.

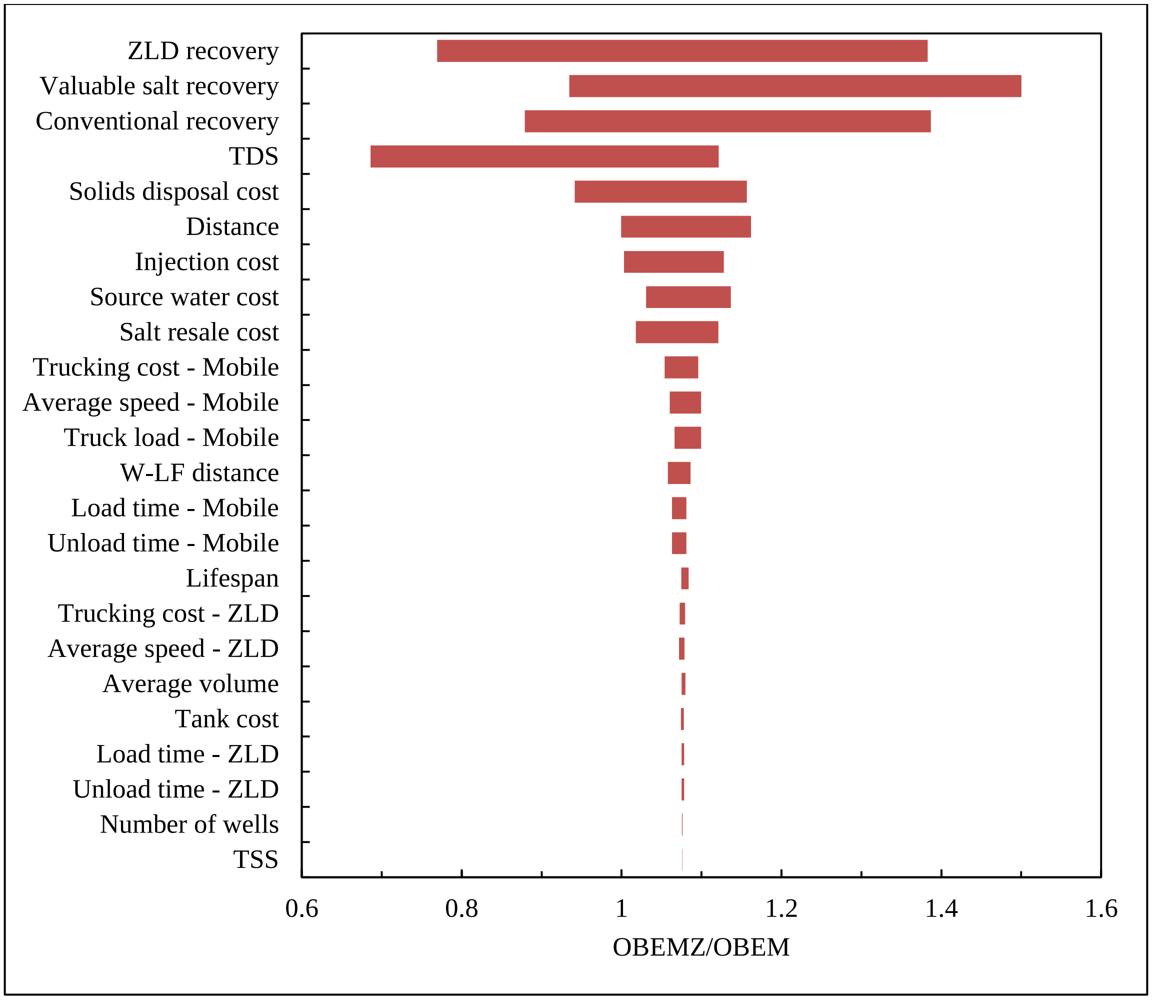

Figure 4.14 Tornado chart for mobile ZLD-to-mobile operator breakeven treatment cost (OBEZM/OBEM).

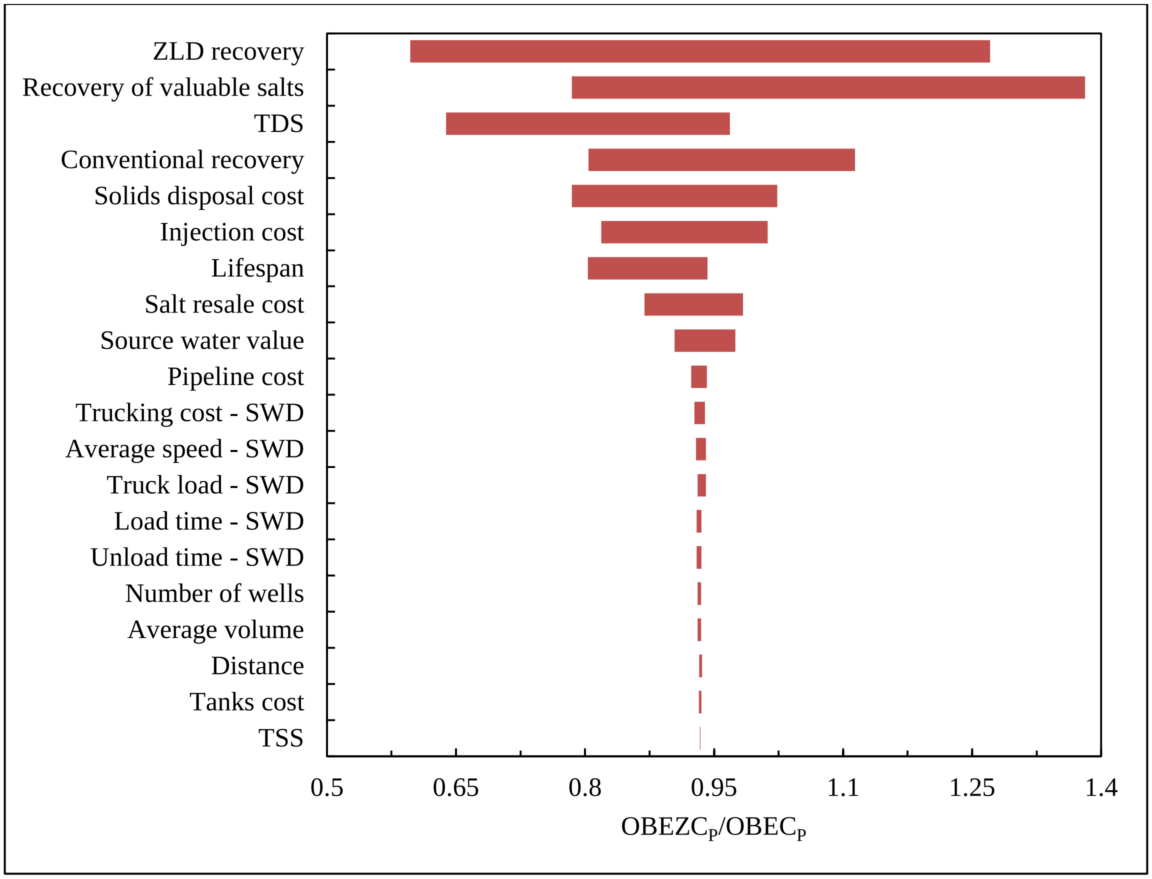

Figure 4.15 Tornado chart for centralized ZLD-to-centralized operator breakeven treatment cost ($OBEZC_P/OBEC_P$).

4.3 Uncertainty analysis

Uncertainty in a model refers to the risk of output error – even with accurate model inputs. For this particular model, the field conditions and inputs are constantly changing and vary case-by-case. It is important to understand variability of the model output. To quantify this uncertainty, a Monte Carlo simulation was conducted. The Monte Carlo simulation is one of the most common uncertainty analyses used (Hammonds, Hoffman, and Bartell 1994). In this analysis, inputs are assigned subjective probability distributions as seen in Table 4.3. Most of these inputs are based off estimated distributions and values. Veil (1997) presented a wide range of cost per ton values for solids disposal cost. These values varied from $12-150 per ton. However, in order to account for hazardous material disposal, such as NORM, the solid disposal maximum of $500 per ton was used. The chosen input uncertainties are meant to model a reasonable distribution of values and are not a perfect depiction of the actual value distributions. In the simulation, input values are randomly chosen based on these probability distributions and the outputs are recorded for many iterations of the random inputs. For this analysis, a Monte Carlo excel add-in, @Risk by Palisade Corporation, was used. The model was iterated 100,000 times in order to determine the probability distributions of the outputs based on the inputs.

Table 4.3 Uncertainty analysis inputs.

Input	Unit	Distribution type	Mean or most probable (Triangular)	P10 - P90 or Min-Max
Treatment cost	*$/bbl*	Uniform	2	1-3
Recovery	*%*	Normal	70	55-85
Distance	*miles*	Uniform	13	1-25
Trucking cost	*$/hr*	Uniform	80	60-100
Pipeline cost	*$/bbl/mile*	Inverse gaussian	0.1	0.02-0.22
Injection cost	*$/bbl*	Triangular	0.9	0.30-1.7
Source water cost	*$/bbl*	Uniform	0.625	0.25-1.00
Lifespan	*years*	Triangular	5	1-10
Volume per well	*bbl/year*	Triangular	31000	3,000-69,000
ZLD treatment cost (high)	*$/bbl*	Uniform	5	1-9
ZLD treatment cost (low)	*$/bbl*	Uniform	2	1-3
ZLD recovery	*%*	Uniform	50	0-100
Valuable salt recovery	*%*	Triangular	10	0-100
TSS	*ppm*	Uniform	500	0-1,000
TDS	*ppm*	Triangular	50,000	15,000-400,000
Solids disposal cost (high)	*$/ton*	Triangular	50	20-500
Solids disposal cost (low)	*$/ton*	Triangular	50	20-100
Salt resale value	*$/ton*	Uniform	92.5	35-150

4.3.1 Produced water management costs

The Monte Carlo simulation is used to calculate the probability distribution of the specified outputs. Figure 4.16 is the 80% confidence interval for SWD injection, mobile, centralized with trucking and centralized with pipeline scenarios. The P10 (10^{th}

percentile), P50 (50th percentile) and P90 (90th percentile) values are displayed on the graph. For the given inputs, there is an 80% probability that the SWD injection cost will be between $1.62 and $2.69 per barrel. The economic competitiveness of treatment and reuse can also be inferred from this graph. Both mobile and centralized treatment and reuse have overall cost per barrels that are competitive with SWD injection. However, centralized with trucking has a limited range of competitive costs. Figure 4.17 includes mobile and centralized ZLD treatment in addition to the data in Figure 4.16. This graph shows how wide the range is for ZLD treatment due to the risk of high disposal and treatment cost. While ZLD does have a competitive cost range, both mobile and centralized ZLD P50 values are above $7 per barrel. Therefore, the conditions for ZLD treatment are highly limited if there is a risk of extreme solids disposal cost or high treatment cost. However, Figure 4.18 shows the same results with the low range of solids disposal and treatment cost. It is important to note that ZLD has become more economic than conventional treatment under such conditions. Therefore, it can be concluded that, with low risk of high treatment or disposal cost, ZLD is much more competitive economically.

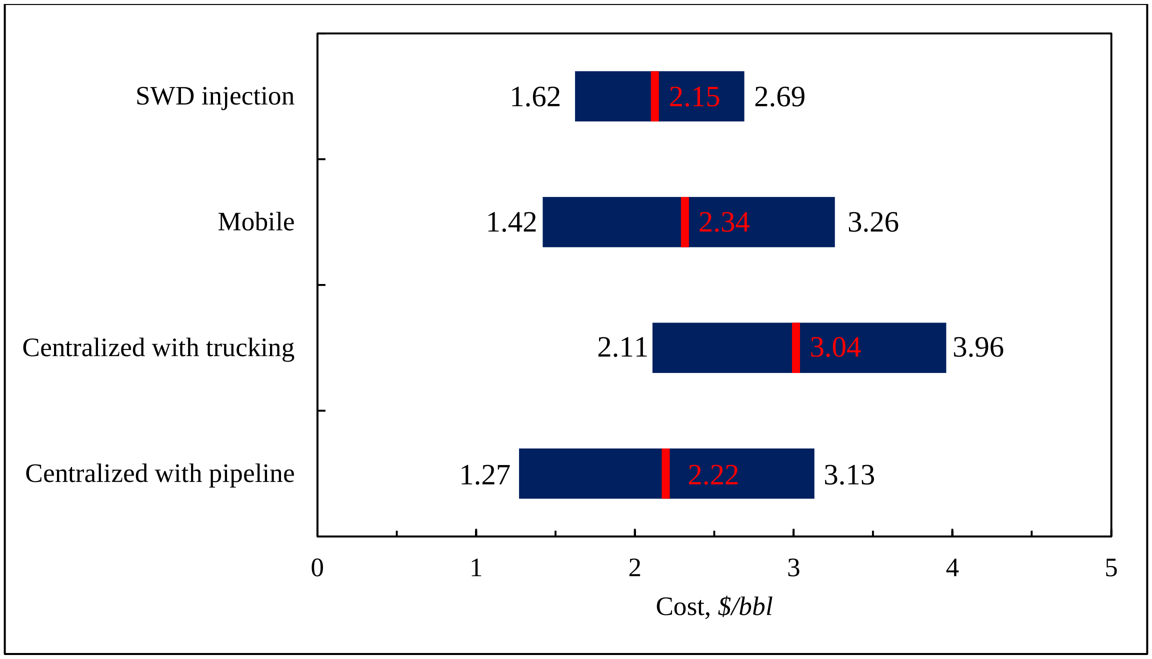

Figure 4.16 Net water management costs per barrel outputs within 80% confidence interval and P10, P50 and P90 values.

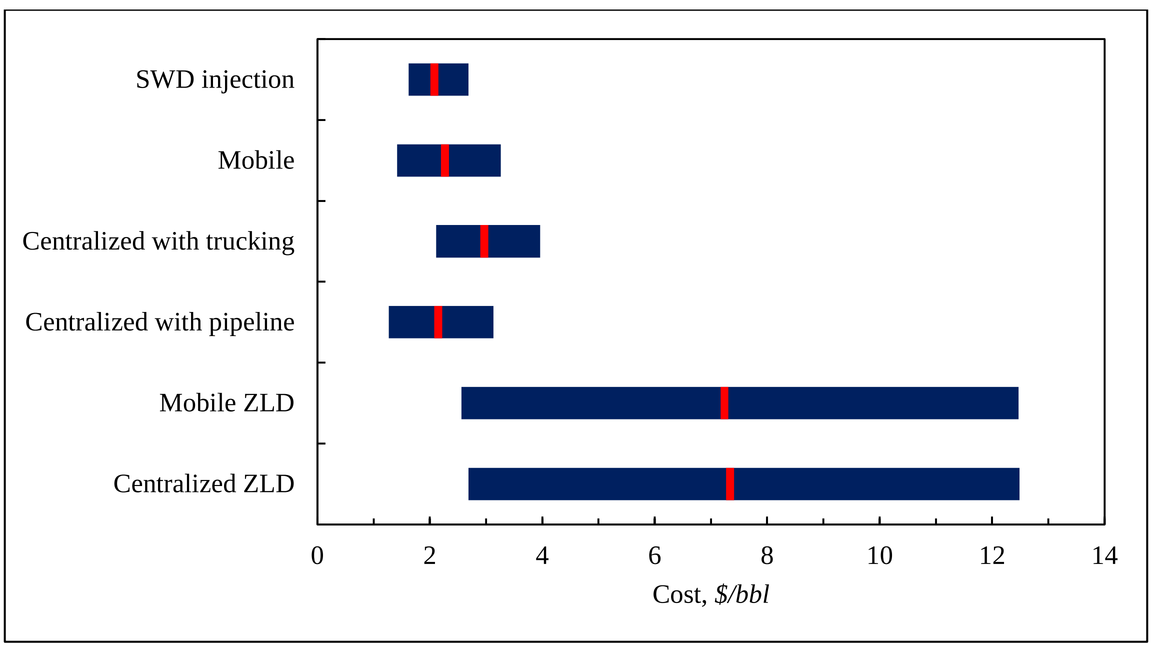

Figure 4.17 Net water management costs with ZLD per barrel outputs within 80% confidence interval. ZLD output is for high range of treatment and solids disposal cost.

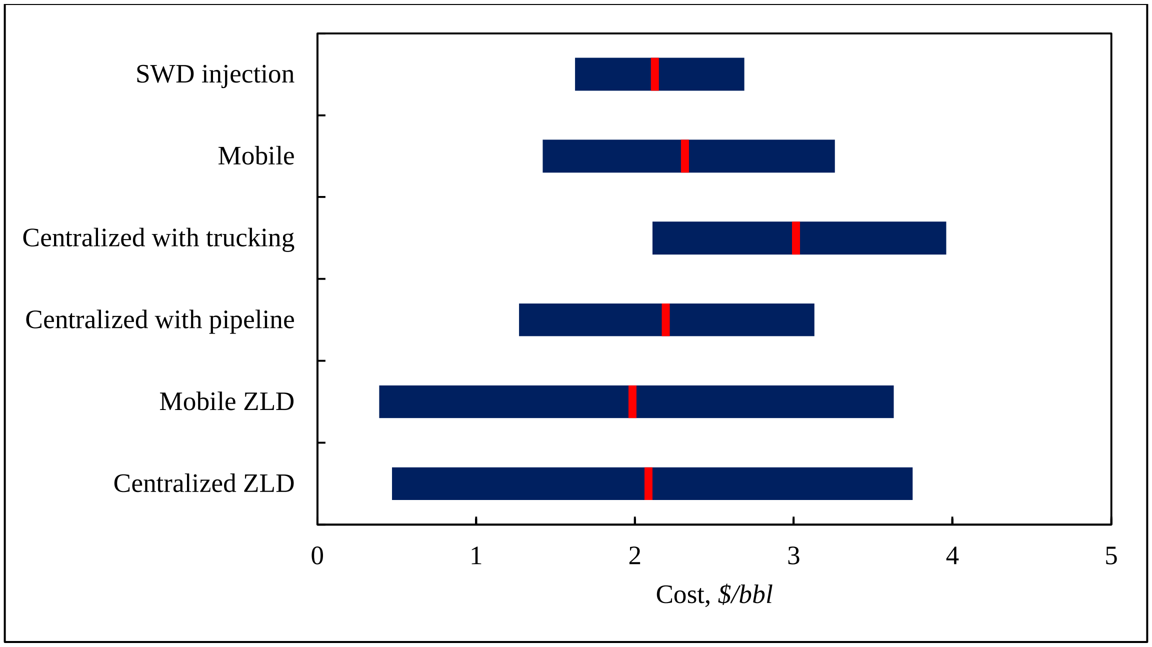

Figure 4.18 Net water management costs with ZLD per barrel outputs within 80% confidence interval. ZLD output is for low range of treatment and solids disposal cost.

4.3.2 Operator breakeven costs

By understanding the output variance of the OBEs, the range of economically feasible treatment costs can be inferred. Figure 4.19 depicts the 80% confidence interval for mobile (OBEM), centralized with trucking ($OBEC_T$) and centralized with pipeline ($OBEC_P$). For the given input conditions, this graph shows that an economical service company's treatment cost is between $1.24-$2.41, $0.53-$1.71 and $1.29-$2.59 per barrel for mobile, centralized with trucking and centralized with pipeline. A higher OBE equates to a greater probability that the service company can treat at that cost. Therefore, a higher OBE is more economically feasible. Centralized with pipeline has the highest range and is the most economic option overall. Figure 4.20 depicts the operator breakeven costs for mobile (OBEZM) and centralized (OBEZC) ZLD. A negative value indicates that a service company would have to pay the operator in order for treatment-and-reuse to be feasible. A negative value is entirely unrealistic. While this graph shows that ZLD can be very uneconomical, there is an upper P90 value of above $2 per barrel. These economics do not bode well for ZLD systems. Most cannot treat water for $2 per barrel. Even if this treatment cost was attainable, only 10% of the time is this treatment cost competitive with SWD injection.

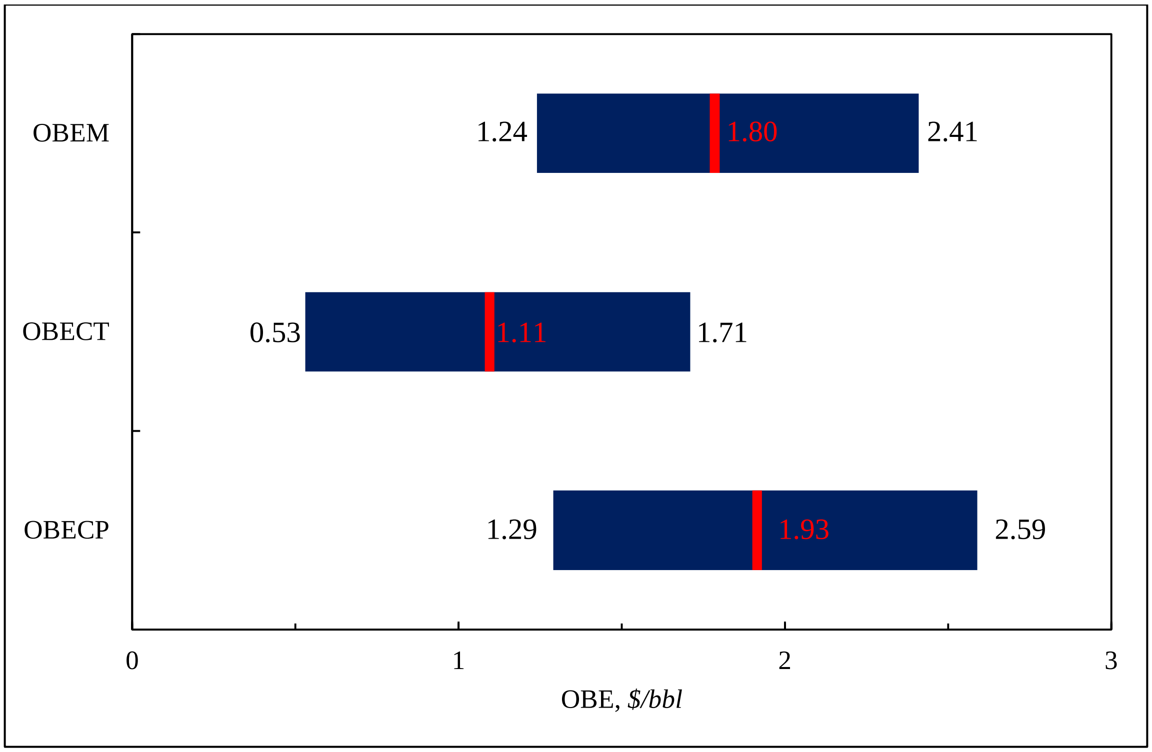

Figure 4.19 Operator breakeven treatment costs per barrel outputs within 80% confidence interval.

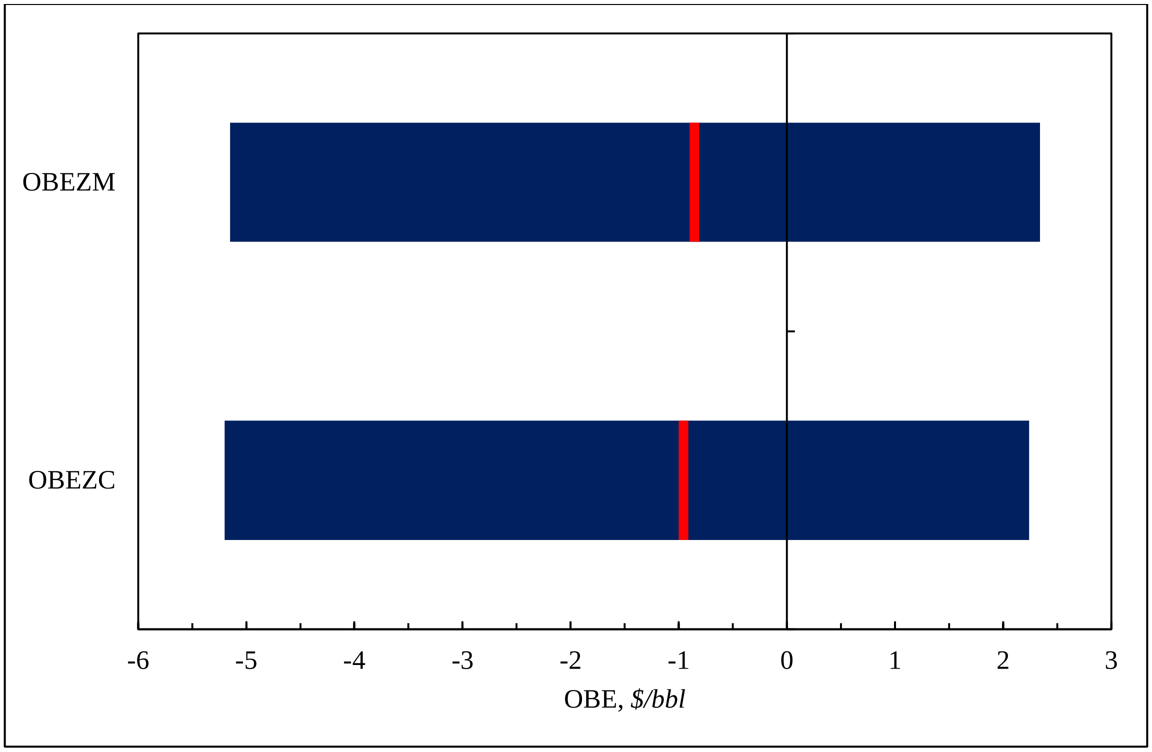

Figure 4.20 Operator breakeven costs per barrel outputs within 80% confidence interval for mobile and centralized ZLD.

4.3.3 Cost ratios

The centralized-to-mobile and ZLD-to-conventional cost ratios that were explored in Sections 4.2.6 and 4.2.9 were also output in the Monte Carlo simulation. This allows for the determination of the probability of centralized being more economical than mobile, and ZLD more economical than conventional. Figure 4.21 displays the 80% confidence interval for the conventional centralized-to-mobile ratio. For the input conditions, it was observed that mobile is more economic than centralized with trucking most of the time. The P90 value is 0.9; therefore, there is a small probability that this ratio will even equal one. On the other hand, centralized with pipeline is more economic than mobile most of the time. The P10 value for this ratio is 1.3, and P90 is 2.6. This means than 80% of the time for the given conditions, centralized with pipeline is between 1.3 and 2.6 times more economic than mobile. As seen in Figure 4.20, ZLD systems have a large range of uneconomic feasibility. Figure 4.22 shows that a majority of the time, mobile and centralized ZLD systems are uneconomic and not competitive with conventional treatment and reuse. However, there is a limited range near the 90th percentile in which a ZLD system can be competitive.

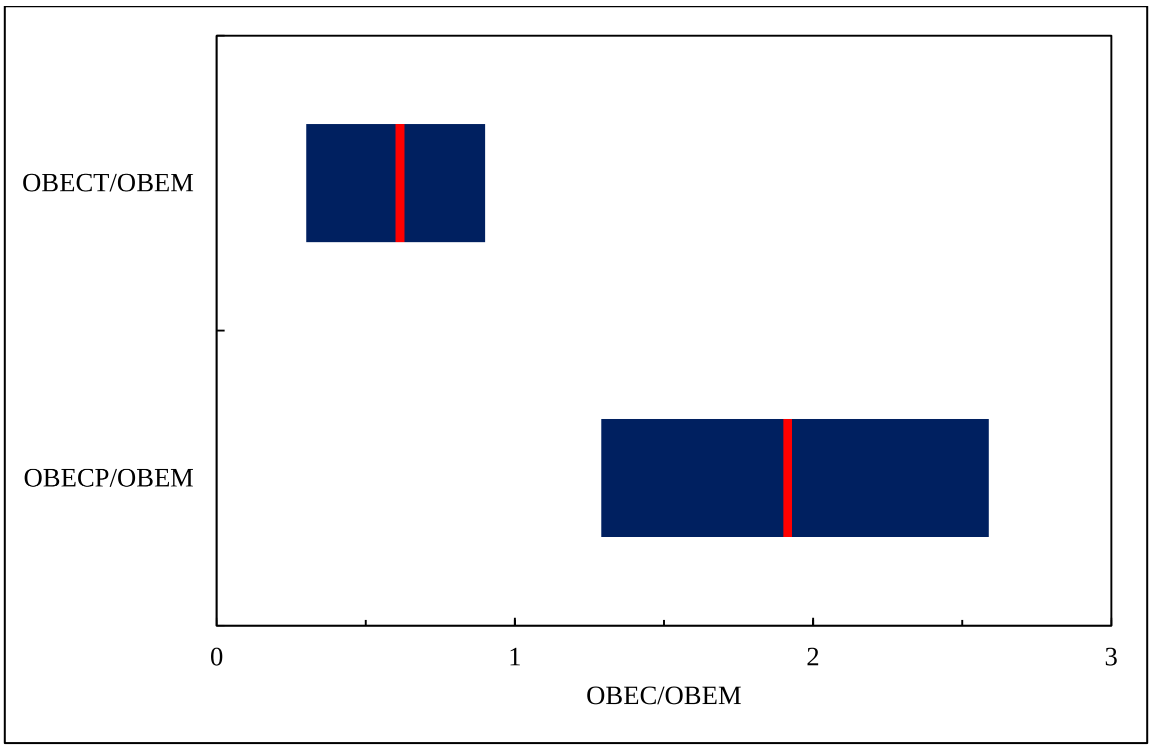

Figure 4.21 Centralized-to-mobile breakeven cost ratios for centralized with trucking ($OBEC_T$) and pipeline ($OBEC_P$).

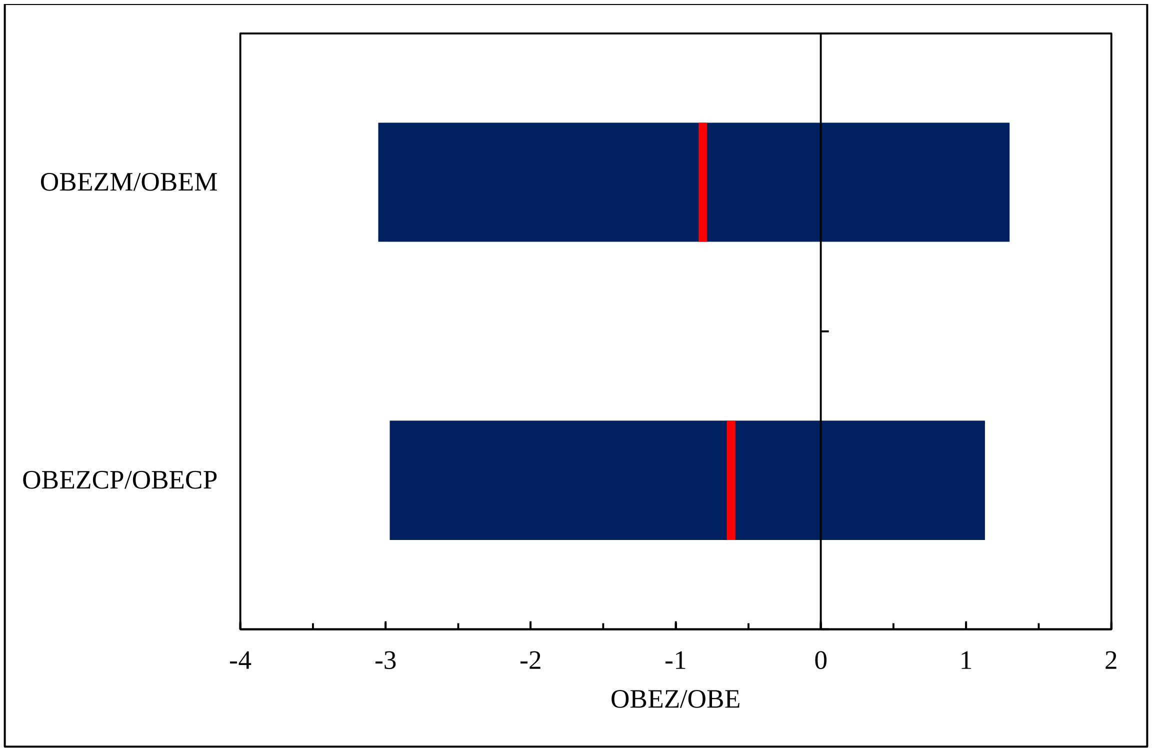

Figure 4.22 ZLD-to-mobile breakeven cost ratios for mobile ZLD (OBEZM/OBEM) and centralized ZLD ($OBEZC_P/OBEC_P$).

5. PERMIAN CASE STUDY

A case study was simulated to demonstrate the use of the model. The location used for the case study is the Permian Basin, which is currently the most active US play (Jacobs 2016). Several companies were contacted and actual field data was requested for this simulation. However, no actual data was available at the time of this study. To conduct the analysis, representative data based on literature findings was used.

Table 5.1 presents Permian Basin cost ranges and their sources from the literature review in Section 2. Note the costs range from sources published within the past 5 years. Minimal treatment refers to basic treatment, such as suspended particle and oil removal, for which the effluent is not high quality, yet could be reused in an E&P process. Extensive treatment refers to advanced treatment, such as desalination, that produces a high-quality effluent and could be sold or reused beneficially. Extensive treatment costs more yet produces a more valuable product.

Table 5.1 Permian cost information for various PW management specific costs.

Type of cost	Range (Max)	Units	Source
Lay flat pipeline	0.02-0.03	*$/bbl/mile*	(Collins 2016, Partners 2011)
Trucking	70-110	*$/hour*	(Cook, Huber, and Webber 2015, Eaton 2014)
Disposal	0.60-2.50	*$/bbl*	(Cook, Huber, and Webber 2015, McCurdy 2011)
Minimal treatment	1.00-2.00	*$/bbl*	(Slutz et al. 2012)
Extensive treatment	3.50-6.25	*$/bbl*	(Slutz et al. 2012)
Ground water	0.16-0.50 (0.80)	*$/bbl*	(Cook, Huber, and Webber 2015)
Fresh water	0.40-0.50	*$/bbl*	(Collins 2016)
Brackish	0.35-0.45	*$/bbl*	(Collins 2016)
Municipal effluent	0.27	*$/bbl*	(Collins 2016)

Permian water production per well data in literature is scarce. For the example, water production per well was estimated from the produced water study conducted by Veil (2015). In this report, he observed that Texas produced 7.43 billion barrels of produced water for 270,082 wells in 2012. This equates to 27,531 barrels produced per well per year. While the assumption that production volumes are uniformly distributed is inaccurate, this annual average production volume was used as a best guess estimate as no other sources of Permian well water production were found. From the sensitivity analysis in Section 4.2, it was observed that the volume produced per well did not have a significant effect on the overall cost per bbl. Therefore, the use of this volume input for a hypothetical case is justified.

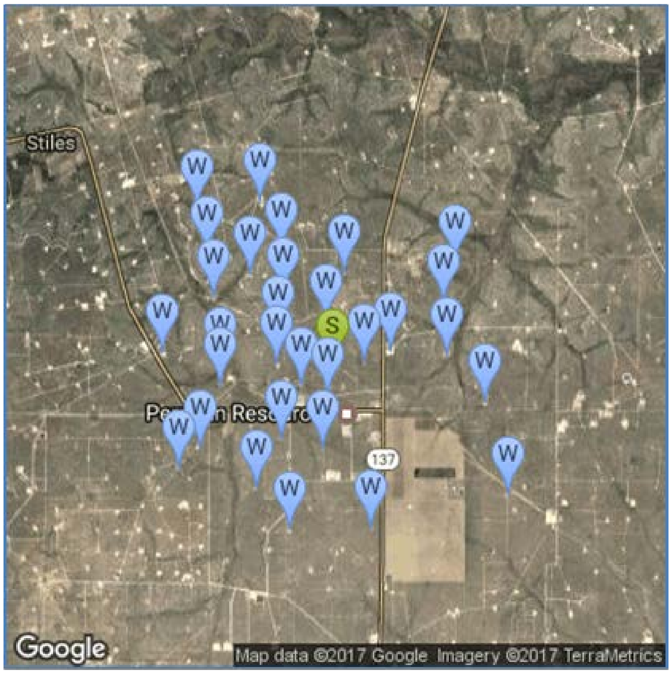

Figure 5.1 Reprinted from Google Maps API of Permian Basin scenario. Each W pin represents a well, and the green S pin is the SWD (Google 2017).

The scenario was simulated for both high and low cost values at 5 and 20 year timespans to provide a short- and long-term output. This was conducted for both minimal and extensive treatment to understand the economic potential for both. Table 5.2 provides the actual inputs used in these scenarios. Recall that the source water cost is used to determine the savings or revenue generated by the treated effluent. To account for the difference in product water quality, the lower brackish water cost range has been used for minimal treatment effluent while the higher fresh water cost range was used for extensive treatment. A high pipeline cost of $0.40 per bbl per mile was used to represent a permanent pipeline rather than a less costly lay flat line.

Table 5.2 Permian Basin scenario general inputs.

Type of input	Low-High		Units
	Minimal	**Extensive**	
Treatment	1.00-2.00	3.50-6.25	*$/bbl*
Source water	0.35-0.45	0.40-0.80	*$/bbl*
Recovery	80		*%*
Pipeline	0.02-0.40		*$/bbl/mile*
Trucking	70-110		*$/hour*
Disposal	0.60-2.50		*$/bbl*
Lifespan	5-20		*years*

The scenario was ran using a 30 well field (See Figure 5.1). The average distance from well to SWD was approximately 4 miles. The results of the simulation are displayed in Table 5.3. Two important conclusions can be made. First, except for the high range of minimal 5 year output, centralized with pipeline is the most economical approach for minimal treatment. Mobile and centralized with pipeline are almost equal at the high range of the 5 year output. Secondly, extensive treatment did not compete with SWD injection. This illustrates the importance of treatment and source water cost. Perhaps the higher extensive treatment cost could be economical if the source water value was higher. The net treatment and reuse savings for minimal treatment are displayed in Figure 5.2 and Figure 5.3. The minimal treatment high range has the highest cost deficit between SWD injection and treatment of $1.53 per bbl. This equates to an overall savings of $25.3 million over 20 years (See Figure 5.3).

Table 5.3 Permian Basin field scenario model outputs for minimal/extensive treatment, low/high cost values and 5 and 20 year lifespans. Lowest outputs are italicized.

Case	Timespan	PW management cost, *$/bbl*			
		SWD Injection	**Mobile**	**Centralized with trucking**	**Centralized with pipeline**
Minimal Low	5 year	1.62	1.29	1.86	*1.08*
	20 year	1.45	1.07	1.69	*0.90*
Minimal High	5 year	3.97	*2.68*	3.62	2.69
	20 year	3.81	2.46	3.45	*2.28*
Extensive Low	5 year	*1.62*	3.75	4.32	3.54
	20 year	*1.45*	3.53	4.15	3.36
Extensive High	5 year	*3.97*	6.65	7.59	6.66
	20 year	*3.81*	6.43	7.42	6.25

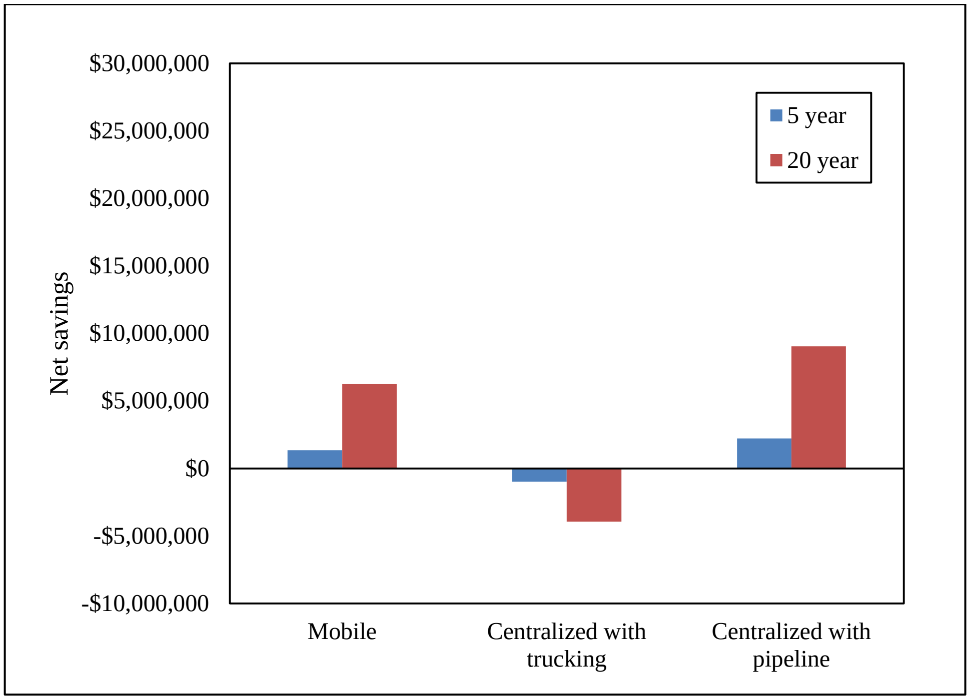

Figure 5.2 Net treatment and reuse savings for minimal treatment with low cost inputs for 5 and 20 year lifespan.

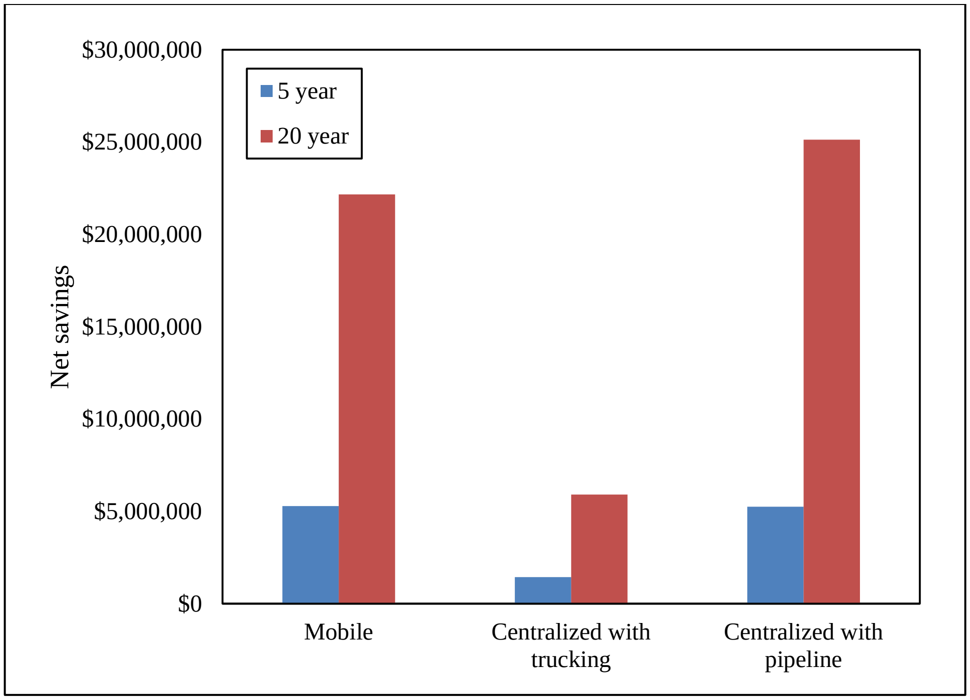

Figure 5.3 Net treatment and reuse savings for minimal treatment with high cost inputs for 5 and 20 year lifespans.

It should be noted that the net savings in these figures are not discounted to reflect the time value of money. In a full economic analysis, net present value of a project is assessed by summing the discounted the cash flows at a discount rate over a set of time periods and subtracting the initial investment. The net cost savings presented will reduce a company's lease operating expense (LOE), thereby, increasing each period cash flow. Therefore, cash flow is a function of LOE, which can be lowered by the net savings. As the entire cash flow is discounted, the discrete cost savings for each respective time period was not discounted.

6. CONCLUSION AND RECOMMENDATIONS

A model was successfully built to address economic uncertainties in the produced water treatment sector of the upstream oil and gas industry. This model can be successfully used to conduct “what if” analyses and was used to address current economic uncertainties in produced water management. To date, an economic evaluation as conducted in this work has not been published. The academic value is addressing PW treatment and reuse uncertainties to which the answers have been either proprietary knowledge, observed but not proven or completely unknown.

6.1 Objective 1 conclusion

The primary factors of treatment and reuse feasibility are treatment cost and recovery, distance, source water, injection and pipeline cost (See Section 4). In general, a lower treatment cost, higher treatment recovery, longer distance, higher injection and source water costs favor treatment and reuse. Longer distances and injection costs lead to an increase in the overall SWD cost, which increases the OBE resulting in a more feasible treatment cost for service companies. Treatment recovery and source water costs are used to determine the amount and value of savings or revenue generated by the product water. The higher the amount and value of this water results in a lower net treatment and reuse cost. The specific cost per bbl for treatment is a significant factor in treatment and reuse feasibility. Recall that treatment and reuse is feasible when the specific cost of treatment is less than or equal to the OBE. For the range of values used in the sensitivity analysis, a feasible treatment cost must be below $3 per barrel, except at extreme distances (Figure 4.5, Figure 4.6 and Figure 4.7).

6.2 Objective 2 conclusion

For mobile treatment, this model utilizes the assumptions that the treated water is either reused or sold on or near the location, neglecting any additional transportation. Given that this assumption is correct, the primary advantage of mobile treatment is minimizing the overall volume of water that must be transported. This is in contrast with centralized treatment where the entire volume must be transported to the centralized facility before any treatment occurs. The advantage of using a pipeline with a centralized facility is that transportation is an initial capital expenditure rather than an annual operating expense from trucking.

Under the given conditions of the sensitivity analysis, mobile was always more economical than centralized with trucking as the $OBEC_T/OBEM$ ratio was less than one for all of the conditions (Figure 4.8). However, centralized with pipeline was more competitive. Shorter well-to-centralized distances, longer project lifespans and lower mobile treatment recoveries were the most significant factors that favored centralized with pipeline over mobile treatment. Lower distance and longer lifespan leads to a reduction in the overall centralized with pipeline net equation, whereas a lower mobile recovery leads to an increase in the overall mobile cost and minimizes mobile's advantage described in the previous paragraph. A scenario with higher treatment recoveries, shorter project lifespans and longer well-to-centralized distances favor mobile treatment.

6.3 Objective 3 conclusion

The primary disadvantage of centralized treatment is transportation of the entire volume of water from the well to the centralized facility. Transportation via trucking is incurred as an annual operating cost. The primary advantage that a pipeline offers is converting this operating expenditure into capital. As the project lifespan increases, this initial capital becomes more diluted and less significant. This pipeline advantage is shown in the sensitivity analysis and uncertainty analysis results where centralized with pipeline is more economical than with trucking. It should be noted that drilling schedule and production uncertainty is not taken into account. While the mid- and long-term economics may favor a pipeline, an operator may choose to truck the water if the drilling schedule is unknown and transportation flexibility is required.

6.4 Objective 4 conclusion

A ZLD, or solid waste treatment, has the benefit of removing liquid waste and producing a solid that could have potential value, in addition to a valuable liquid permeate. However, this advantage is dependent upon value of the product and whether or not that product exists (water and salt recovery). The disadvantage of ZLD is a risk of high treatment cost and extreme solids disposal cost. As a ZLD system often requires great energy input, this induces the risk of high cost. However, if a system can tap into alternative sources of energy, such as flue gas onsite, the cost of treatment could be reduced. PW can contain toxic material; for example, NORM can be present at trace concentrations in certain regions. When dissolved solids are concentration to a solid waste, these toxins become significant, and hazardous waste handling and disposal can be extremely expensive.

Upon the analysis, this wide range of treatment and solids disposal cost and potential for valuable solid and liquid product was taken into account. Low liquid and valuable salt recoveries and high treatment and disposal costs resulted in poor economics. Therefore, a ZLD treatment system can be economically competitive contingent upon specific conditions: low risk of extreme treatment and solids disposal costs and the system must produce a water and/or solid product.

6.5 Recommendations

The results from the analysis of this model suggest that treatment and reuse can be economically competitive with SWD injection. For the range of conditions modeled in the evaluation, it was observed that the specific cost of treatment has a significant impact on overall feasibility. Therefore, a service company seeking to enter the market should strive to reduce the treatment cost per barrel significantly. It should not exceed more than $3.00 per bbl for conventional and ZLD treatment approaches. An ideal treatment cost is $2.00 per bbl or less.

Utilization of pipelines for centralized treatment was determined to the most advantageous strategy. If a company has the option, pipeline infrastructure should be heavily considered. However, it should be noted that this model is purely economic and does not consider additional pipeline uncertainties such as permitting, right of way acquisition or leakage risk. Simply, the conversion of an annual trucking expense into an initial CAPEX proved economic in this model at mid to long project lifespans.

A company seeking to use ZLD treatment should proceed with caution. The risk of high treatment cost and high solids disposal cost induces the uncertainty of the treatment being extremely costly. The primary economic drivers determined from this model were water and salt recovery. Therefore, an economic ZLD system should produce some form of product, whether that is liquid, salt or both.

6.6 Observations from the perspective of an environmental engineer

The author has studied produced water and worked in and around oil and gas for the past three and a half years. During which time, he has noticed a conundrum in the PW sector. That is, the petroleum engineers who make water management decisions typically have very little water knowledge; the engineers who design produced water treatment typically have very little oil and gas knowledge. This knowledge gap is a hurdle that must be overcome for effective PW treatment and reuse.

In petroleum engineering classes, water production is feared because water has “no value” relative to oil or gas. The reason this is taught is that the more water a well produces, the less the production of hydrocarbons – in fact, water breakthrough can potentially indicate the end of a horizontal well’s life. While it is true that water production inhibits that of oil, we should stray from the notion that water has no value and reconsider the way we view water in the upstream oil and gas industry. More and more oil and gas companies are realizing that they are in the water business just as much as, if not more than, they are in that of oil and gas – given the enormous water production in certain regions. The key to a sustainable business plan is cost effective water management. If water management can be leveraged to produce greater profits, whether through treated water resale and/or increased economic limits of producing wells, both the company's budget and the environment will benefit.

Water treatment design can involve a combination of engineering disciplines, such as, civil, chemical, mechanical and electrical. Water and wastewater treatment conventionally falls within the civil realm providing a public service to provide clean tap water and remove pathogens from sewage. The idea of oil and gas PW treatment began only a few decades ago. Therefore, most water treatment professionals have experience with either municipal or other industrial water, not upstream oil and gas. In order to provide better service, identify new treatment and reuse strategies and make PW management more effective, water professionals should gain more knowledge of oil and gas processes. For example, if treated PW is to be used for water flooding or polymer flooding, the treatment company should know what is involved in such a process in order to identify and remove water constituents that might interact with the formation or polymers.

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APPENDIX A: SENSITIVITY ANALYSIS SUPPORTING DATA

The following tables contain the supporting data from the sensitivity analysis described in Section 4. Data from these tables was used to construct the visual tornado graphs. This data is provided for clarification as the tornado graphs are ambiguous if trying to determine the exact percentage of change of each minimum and maximum variable.

Table A.1 Sensitivity analysis data for SWD injection scenario.

	Minimum			Maximum			
	Output		Input	Output		Input	Input
Input name	**Value**	**Change (%)**	**Value**	**Value**	**Change (%)**	**Value**	**Base Value**
Distance	1.64	-27.64%	5	3.39	49.76%	75	30
Injection cost	1.66	-26.54%	0.3	2.86	26.54%	1.5	0.9
Trucking cost	2.05	-9.21%	50	2.47	9.21%	70	60
Average speed	2.11	-6.63%	50	2.51	11.06%	30	40
Truck load	2.16	-4.25%	130	2.51	11.06%	100	120
Lifespan	2.22	-1.97%	5	2.48	9.83%	1	3
Load time	2.14	-5.53%	0.25	2.31	2.21%	0.6	0.5
Unload time	2.14	-5.53%	0.25	2.31	2.21%	0.6	0.5
Average volume	2.22	-1.64%	45000	2.37	4.91%	15000	30000
Tank cost	2.21	-2.46%	5000	2.32	2.46%	15000	10000
Number of wells	2.26	-0.06%	37.5	2.26	0.00%	25	50

Table A.2 Sensitivity analysis data for mobile conventional treatment scenario**.**

Input Name	Minimum			Maximum			Input
	Output		Input	Output		Input	
	Value	Change (%)	Value	Value	Change (%)	Value	Base Value
Recovery	1.77	-23.63%	0.85	2.86	23.63%	0.55	0.7
Treatment	1.82	-21.58%	2	2.82	21.58%	3	2.5
Source water cost	1.97	-15.10%	2	2.67	15.11%	1	1.5
Lifespan	2.23	-3.84%	5	2.76	19.18%	1	3
Distance	2.13	-8.09%	5	2.65	14.57%	75	30
Injection cost	2.14	-7.77%	0.3	2.50	7.77%	1.5	0.9
Average volume	2.24	-3.20%	45000	2.54	9.59%	15000	30000
Tank cost	2.21	-4.79%	5000	2.43	4.80%	15000	10000
Trucking cost	2.25	-2.70%	50	2.38	2.70%	70	60
Average speed	2.27	-1.94%	50	2.39	3.24%	30	40
Truck load	2.29	-1.24%	130	2.39	3.24%	100	120
Load time	2.28	-1.62%	0.25	2.33	0.65%	0.6	0.5
Unload time	2.28	-1.62%	0.25	2.33	0.65%	0.6	0.5
Number of wells	2.31	-0.13%	37.5	2.32	0.00%	75	50

Table A.3 Sensitivity analysis data for centralized with trucking conventional treatment.

Input Name	Minimum			Maximum			Input
	Output		Input	Output		Input	Input
	Value	Change (%)	Value	Value	Change (%)	Value	Base Value
Distance	2.46	-20.26%	5	4.21	36.46%	75	30
Treatment	2.59	-16.21%	2	3.59	16.20%	3	2.5
Recovery	2.73	-11.67%	0.85	3.45	11.67%	0.55	0.7
Source water cost	2.74	-11.34%	2	3.44	11.34%	1	1.5
Trucking cost	2.88	-6.75%	50	3.29	6.75%	70	60
Average speed	2.94	-4.86%	50	3.34	8.10%	30	40
Injection cost	2.91	-5.83%	0.3	3.27	5.83%	1.5	0.9
Truck load	2.99	-3.12%	130	3.34	8.10%	100	120
Lifespan	3.04	-1.50%	5	3.32	7.49%	1	3
Load time	2.96	-4.05%	0.25	3.14	1.62%	0.6	0.5
Unload time	2.96	-4.05%	0.25	3.14	1.62%	0.6	0.5
Average volume	3.05	-1.25%	45000	3.20	3.74%	15000	30000
Tank cost	3.03	-1.87%	5000	3.14	1.87%	15000	10000
Number of wells	3.08	-0.06%	62.5	3.09	0.14%	25	50

Table A.4 Sensitivity analysis data for centralized with pipeline conventional treatment.

Input Name	Minimum			Maximum			Input
	Output		Input	Output		Input	Input
	Value	Change (%)	Value	Value	Change (%)	Value	Base Value
Lifespan	2.21	-12.87%	5	4.17	64.33%	1	3
Distance	1.95	-23.01%	5	3.59	41.41%	75	30
Treatment	2.04	-19.72%	2	3.04	19.72%	3	2.5
Recovery	2.18	-14.20%	0.85	2.90	14.20%	0.55	0.7
Source water cost	2.19	-13.81%	2	2.89	13.80%	1	1.5
Pipeline cost	2.24	-11.83%	0.04	2.84	11.83%	0.1	0.07
Injection cost	2.36	-7.10%	0.3	2.72	7.10%	1.5	0.9
Average volume	2.50	-1.52%	45000	2.65	4.56%	15000	30000
Tank cost	2.48	-2.28%	5000	2.59	2.28%	15000	10000
Number of wells	2.53	-0.07%	62.5	2.54	0.17%	25	50

Table A.5 Sensitivity analysis data for mobile operator breakeven treatment cost (OBEM).

Input Name	Minimum Output Value	Minimum Output Change (%)	Minimum Input Value	Maximum Output Value	Maximum Output Change (%)	Maximum Input Value	Input Base Value
Distance	2.01	-17.90%	5	3.23	32.22%	75	30
Mobile recovery	1.90	-22.40%	0.55	2.99	22.40%	0.85	0.7
Injection cost	2.02	-17.19%	0.3	2.86	17.19%	1.5	0.9
Source water cost	2.09	-14.32%	1	2.79	14.32%	2	1.5
Trucking cost	2.30	-5.97%	50	2.59	5.97%	70	60
Average speed	2.34	-4.30%	50	2.62	7.16%	30	40
Lifespan	2.22	-9.09%	1	2.49	1.82%	5	3
Truck load	2.38	-2.75%	130	2.62	7.16%	100	120
Average volume	2.33	-4.55%	15000	2.48	1.52%	45000	30000
Load time	2.36	-3.58%	0.25	2.48	1.43%	0.6	0.5
Unload time	2.36	-3.58%	0.25	2.48	1.43%	0.6	0.5
Tank cost	2.39	-2.27%	15000	2.50	2.27%	5000	10000
Number of wells	2.44	0.00%	75	2.45	0.06%	37.5	50

Table A.6 Sensitivity analysis data for centralized with trucking operator breakeven treatment cost ($OBEC_T$).

Input Name	Minimum Output Value	Minimum Output Change (%)	Minimum Input Value	Maximum Output Value	Maximum Output Change (%)	Maximum Input Value	Input Base Value
Injection cost	1.26	-25.07%	0.3	2.10	25.07%	1.5	0.9
Recovery	1.32	-21.49%	0.55	2.04	21.49%	0.85	0.7
Source water cost	1.33	-20.89%	1	2.03	20.89%	2	1.5
Lifespan	1.67	-0.53%	1	1.68	0.11%	5	3
Number of wells	1.67	-0.27%	25	1.68	0.09%	75	50
Average volume	1.67	-0.27%	15000	1.68	0.09%	45000	30000
Tank cost	1.67	-0.13%	15000	1.68	0.13%	5000	10000

Table A.7 Sensitivity analysis for centralized with pipeline operator breakeven treatment cost ($OBEC_P$).

	Minimum			Maximum			
	Output		Input	Output		Input	Input
Input Name	**Value**	**Change (%)**	**Value**	**Value**	**Change (%)**	**Value**	**Base Value**
Lifespan	0.82	-63.31%	1	2.51	12.66%	5	3
Injection cost	1.81	-18.87%	0.3	2.65	18.87%	1.5	0.9
Recovery	1.87	-16.18%	0.55	2.59	16.18%	0.85	0.7
Source water cost	1.88	-15.73%	1	2.58	15.73%	2	1.5
Pipeline cost	1.93	-13.48%	0.1	2.53	13.48%	0.04	0.07
Trucking cost	2.02	-9.36%	50	2.43	9.36%	70	60
Average speed	2.08	-6.74%	50	2.48	11.23%	30	40
Truck load	2.13	-4.32%	130	2.48	11.23%	100	120
Load time	2.10	-5.62%	0.25	2.28	2.25%	0.6	0.5
Unload time	2.10	-5.62%	0.25	2.28	2.25%	0.6	0.5
Distance	2.18	-1.87%	5	2.30	3.37%	75	30
Number of wells	2.22	-0.20%	25	2.23	0.07%	75	50
Average volume	2.22	-0.20%	15000	2.23	0.07%	45000	30000
Tank cost	2.22	-0.10%	15000	2.23	0.10%	5000	10000

Table A.8 Sensitivity analysis data for the $OBEC_T$/OBEM ratio.

Input Name	Minimum			Maximum			Input Base Value
	Output		Input	Output		Input	
	Value	Change (%)	Value	Value	Change (%)	Value	
Distance	0.52	-24.37%	75	0.84	21.81%	5	30
Injection cost	0.62	-9.52%	0.3	0.73	6.72%	1.5	0.9
Source water cost	0.63	-7.66%	1	0.72	5.74%	2	1.5
Trucking cost	0.65	-5.63%	70	0.73	6.35%	50	60
Average speed	0.64	-6.68%	30	0.72	4.49%	50	40
Lifepsan	0.67	-1.68%	5	0.75	9.42%	1	3
Truck load	0.64	-6.68%	100	0.71	2.83%	130	120
Average volume	0.68	-1.41%	45000	0.72	4.49%	15000	30000
Load time	0.68	-1.41%	0.6	0.71	3.71%	0.25	0.5
Unload time	0.68	-1.41%	0.6	0.71	3.71%	0.25	0.5
Tank cost	0.67	-2.09%	5000	0.70	2.19%	15000	10000
Recovery	0.68	-0.75%	0.85	0.69	1.18%	0.55	0.7
Number of wells	0.68	-0.27%	25	0.69	0.09%	75	50

Table A.9 Sensitivity analysis data for $OBEC_P$/OBEM ratio.

	Minimum			Maximum			
	Output		Input	Output		Input	Input
Input Name	**Value**	**Change (%)**	**Value**	**Value**	**Change (%)**	**Value**	**Base Value**
Lifespan	0.37	-59.63%	1	1.01	10.65%	5	3
Distance	0.71	-21.82%	75	1.09	19.52%	5	30
Pipeline cost	0.79	-13.48%	0.1	1.03	13.48%	0.04	0.07
Recovery	0.86	-5.09%	0.85	0.98	8.02%	0.55	0.7
Trucking cost	0.88	-3.61%	50	0.94	3.20%	70	60
Average speed	0.89	-2.55%	50	0.95	3.80%	30	40
Average volume	0.90	-1.43%	45000	0.95	4.55%	15000	30000
Truck load	0.90	-1.61%	130	0.95	3.80%	100	120
Tank cost	0.89	-2.13%	5000	0.93	2.22%	15000	10000
Injection cost	0.89	-2.04%	0.3	0.92	1.44%	1.5	0.9
Load time	0.89	-2.11%	0.25	0.92	0.80%	0.6	0.5
Unload time	0.89	-2.11%	0.25	0.92	0.80%	0.6	0.5
Source water cost	0.90	-1.64%	1	0.92	1.23%	2	1.5
Number of wells	0.91	-0.20%	25	0.91	0.07%	75	50

Table A.10 Sensitivity analysis data for mobile ZLD treatment.

Input Name	Minimum Output Value	Minimum Output Change (%)	Minimum Input Value	Maximum Output Value	Maximum Output Change (%)	Maximum Input Value	Input Base Value
ZLD treatment cost	0.63	-86.34%	1	8.63	86.34%	9	5
ZLD recovery	3.88	-16.19%	1	5.38	16.19%	0	0.5
Recovery of valuable salt	3.59	-22.56%	1	4.98	7.52%	0	0.25
TDS	4.52	-2.40%	15000	5.59	20.57%	350000	50000
Lifespan	4.54	-1.92%	5	5.08	9.59%	1	3
Solids disposal cost	4.43	-4.30%	20	4.96	7.16%	100	50
Source water cost	4.38	-5.40%	2	4.88	5.40%	1	1.5
Average volume	4.56	-1.60%	45000	4.85	4.80%	15000	30000
Salt resale value	4.52	-2.39%	150	4.78	3.10%	35	100
Tank cost	4.52	-2.40%	5000	4.74	2.40%	15000	10000
W-LF distance	4.61	-0.54%	5	4.68	0.97%	75	30
Trucking cost	4.62	-0.18%	50	4.64	0.18%	70	60
Average speed	4.63	-0.13%	50	4.64	0.22%	30	40
Load time	4.63	-0.11%	0.25	4.63	0.04%	0.6	0.5
Unload time	4.63	-0.11%	0.25	4.63	0.04%	0.6	0.5
TSS	4.63	-0.03%	0	4.63	0.03%	1000	500

Table A.11 Sensitivity analysis data for centralized ZLD treatment.

	Minimum			Maximum			
	Output		Input	Output		Input	Input
Input Name	Value	Change (%)	Value	Value	Change (%)	Value	Base Value
ZLD treatment cost	1.18	-77.18%	1	9.18	77.18%	9	5
Lifespan	4.85	-6.35%	5	6.83	31.73%	1	3
Distance	4.60	-11.26%	5	6.23	20.26%	75	30
ZLD recovery	4.43	-14.47%	1	5.93	14.47%	0	0.5
Recovery of valuable salt	4.19	-19.21%	1	5.51	6.40%	0	0.25
TDS	5.11	-1.48%	15000	5.84	12.68%	350000	50000
Pipeline cost	4.88	-5.79%	0.04	5.48	5.79%	0.1	0.07
Solids disposal cost	4.98	-3.84%	20	5.51	6.40%	100	50
Source water cost	4.93	-4.82%	2	5.43	4.82%	1	1.5
Salt resale value	5.07	-2.13%	150	5.33	2.77%	35	100
Average volume	5.14	-0.79%	45000	5.31	2.36%	15000	30000
Tank cost	5.12	-1.18%	5000	5.24	1.18%	15000	10000
Number of wells	5.18	-0.07%	75	5.19	0.21%	25	50
TSS	5.18	-0.02%	0	5.18	0.02%	1000	500

Table A.12 Sensitivity analysis data for mobile ZLD operator breakeven treatment cost (OBEZM).

	Minimum			Maximum			
	Output		Input	Output		Input	Input
Input Name	**Value**	**Change (%)**	**Value**	**Value**	**Change (%)**	**Value**	**Base Value**
Distance	2.00	-23.78%	5	3.75	42.80%	75	30
ZLD recovery	1.88	-28.53%	0	3.38	28.53%	1	0.5
Recovery of valuable salt	2.28	-13.26%	0	3.67	39.77%	1	0.25
Injection cost	2.03	-22.83%	0.3	3.23	22.83%	1.5	0.9
TDS	1.68	-36.25%	350000	2.74	4.23%	15000	50000
Solids disposal cost	2.30	-12.63%	100	2.83	7.58%	20	50
Source water cost	2.38	-9.51%	1	2.88	9.51%	2	1.5
Trucking Cost - SWD	2.42	-7.93%	50	2.84	7.93%	70	60
Average speed - SWD	2.48	-5.71%	50	2.88	9.51%	30	40
Truck load - SWD	2.53	-3.66%	130	2.88	9.51%	100	120
Lifespan	2.41	-8.45%	1	2.67	1.69%	5	3
Salt resale value	2.48	-5.47%	35	2.74	4.21%	150	100
Load time - SWD	2.50	-4.76%	0.25	2.68	1.90%	0.6	0.5
Unload time - SWD	2.50	-4.76%	0.25	2.68	1.90%	0.6	0.5
Average volume	2.52	-4.23%	15000	2.67	1.41%	45000	30000
Tank cost	2.57	-2.11%	15000	2.68	2.11%	5000	10000
W-LF distance	2.58	-1.70%	75	2.65	0.95%	5	30
Trucking cost	2.62	-0.32%	70	2.64	0.32%	50	60
Average speed - ZLD	2.62	-0.38%	30	2.63	0.23%	50	40
Load time - ZLD	2.63	-0.08%	0.6	2.63	0.19%	0.25	0.5
Unload time - ZLD	2.63	-0.08%	0.6	2.63	0.19%	0.25	0.5
TSS	2.63	-0.06%	1000	2.63	0.06%	0	500

Table A.13 Sensitivity analysis data for centralized ZLD operator breakeven treatment cost (OBEZC).

Input Name	Minimum			Maximum			Input
	Output		Input	Output		Input	Input
	Value	Change (%)	Value	Value	Change (%)	Value	Base Value
Lifespan	0.66	-68.43%	1	2.36	13.69%	5	3
ZLD recovery	1.33	-36.09%	0	2.83	36.09%	1	0.5
Recovery of valuable salts	1.75	-15.97%	0	3.07	47.90%	1	0.25
Injection cost	1.48	-28.87%	0.3	2.68	28.87%	1.5	0.9
TDS	1.42	-31.62%	350000	2.15	3.69%	15000	50000
Pipeline cost	1.78	-14.44%	0.1	2.38	14.44%	0.04	0.07
Solids disposal	1.75	-15.97%	100	2.28	9.58%	20	50
Source water cost	1.83	-12.03%	1	2.33	12.03%	2	1.5
Trucking cost	1.87	-10.02%	50	2.29	10.02%	70	60
Average speed	1.93	-7.22%	50	2.33	12.03%	30	40
Truck load	1.98	-4.63%	130	2.33	12.03%	100	120
Salt resale	1.93	-6.92%	35	2.19	5.32%	150	100
Load time	1.95	-6.01%	0.25	2.13	2.41%	0.6	0.5
Unload time	1.95	-6.01%	0.25	2.13	2.41%	0.6	0.5
Distance	2.04	-2.00%	5	2.15	3.61%	75	30
Number of wells	2.07	-0.53%	25	2.08	0.18%	75	50
Average volume	2.07	-0.53%	15000	2.08	0.18%	45000	30000
Tank cost	2.07	-0.27%	15000	2.08	0.27%	5000	10000
TSS	2.08	-0.05%	1000	2.08	0.05%	0	500

Table A.14 Sensitivity analysis data for mobile ZLD to conventional operator breakeven treatment cost ratio (OBEZM/OBEM).

	Minimum			Maximum			
	Output		Input	Output		Input	Input
Input Name	**Value**	**Change (%)**	**Value**	**Value**	**Change (%)**	**Value**	**Base Value**
ZLD recovery	0.77	-28.53%	0	1.38	28.54%	1	0.5
Recovery of valuable salt	0.93	-13.25%	0	1.50	39.77%	1	0.25
Conventional recovery	0.88	-18.30%	0.85	1.39	28.88%	0.55	0.7
TDS	0.69	-36.25%	350000	1.12	4.23%	15000	50000
Solids disposal cost	0.94	-12.62%	100	1.16	7.58%	20	50
Distance	1.00	-7.15%	5	1.16	8.00%	75	30
Injection cost	1.00	-6.81%	0.3	1.13	4.82%	1.5	0.9
Source water cost	1.03	-4.20%	2	1.14	5.62%	1	1.5
Salt resale value	1.02	-5.47%	35	1.12	4.21%	150	100
Trucking Cost - Mobile	1.05	-2.08%	50	1.10	1.85%	70	60
Average speed - Mobile	1.06	-1.47%	50	1.10	2.20%	30	40
Truck load -Mobile	1.07	-0.93%	130	1.10	2.20%	100	120
W-LF distance	1.06	-1.70%	75	1.09	0.95%	5	30
Load time - Mobile	1.06	-1.22%	0.25	1.08	0.47%	0.6	0.5
Unload Time - Mobile	1.06	-1.22%	0.25	1.08	0.47%	0.6	0.5
Lifespan	1.07	-0.12%	5	1.08	0.71%	1	3
Trucking cost - ZLD	1.07	-0.31%	70	1.08	0.32%	50	60
Average speed - ZLD	1.07	-0.38%	30	1.08	0.23%	50	40
Average volume	1.07	-0.10%	45000	1.08	0.34%	15000	30000
Tank cost	1.07	-0.15%	5000	1.08	0.17%	15000	10000
Load time - ZLD	1.07	-0.07%	0.6	1.08	0.19%	0.25	0.5
Unload time - ZLD	1.07	-0.07%	0.6	1.08	0.19%	0.25	0.5
TSS	1.07	-0.06%	1000	1.08	0.06%	0	500
Number of wells	1.07	-0.06%	37.5	1.08	0.00%	75	50

Table A.15 Sensitivity analysis data for centralized with pipeline ZLD to conventional operator breakeven treatment cost ratio ($OBEZC_P/OBEC_P$).

	Minimum			Maximum			
	Output		Input	Output		Input	Input
Input Name	**Value**	**Change (%)**	**Value**	**Value**	**Change (%)**	**Value**	**Base Value**
ZLD recovery	0.60	-36.09%	0	1.27	36.09%	1	0.5
Recovery of valuable salt	0.78	-15.97%	0	1.38	47.91%	1	0.25
TDS	0.64	-31.62%	350000	0.97	3.69%	15000	50000
Centralized recovery	0.80	-13.92%	0.85	1.11	19.30%	0.55	0.7
Solids disposal cost	0.78	-15.97%	100	1.02	9.58%	20	50
Injection cost	0.82	-12.32%	0.3	1.01	8.41%	1.5	0.9
Lifespan	0.80	-13.97%	1	0.94	0.91%	5	3
Salt resale cost	0.87	-6.92%	35	0.98	5.32%	150	100
Source water cost	0.90	-3.19%	2	0.97	4.39%	1	1.5
Pipeline cost	0.92	-1.10%	0.1	0.94	0.84%	0.04	0.07
Trucking cost	0.93	-0.73%	50	0.94	0.61%	70	60
Average speed	0.93	-0.51%	50	0.94	0.72%	30	40
Truck load	0.93	-0.32%	130	0.94	0.72%	100	120
Load time	0.93	-0.42%	0.25	0.94	0.16%	0.6	0.5
Unload time	0.93	-0.42%	0.25	0.94	0.16%	0.6	0.5
Number of wells	0.93	-0.33%	25	0.93	0.11%	75	50
Average volume	0.93	-0.33%	15000	0.93	0.11%	45000	30000
Distance	0.93	-0.13%	5	0.94	0.23%	75	30
Tank cost	0.93	-0.17%	15000	0.94	0.17%	5000	10000
TSS	0.93	-0.05%	1000	0.93	0.06%	0	500

APPENDIX B: PROGRAM DEVELOPMENT

Introduction

The original model was developed in a spreadsheet using Microsoft Excel. A spreadsheet-based platform was chosen due to simplicity and ability to use programs, such as Palisade's TopRank and @Risk, to evaluate the model. However, only using spreadsheet calculations limited the overall ability of the model.

Advancement into an actual computer program would expand the capabilities and functionality of the model. Excel Visual Basic for Application (VBA) was used as the subsequent platform due to the author's knowledge of this language and ease of transference from spreadsheet to macro.

Subs and functions

Excel VBA is a programming language built into the "Developer" layer of Microsoft Excel and other Office programs. It is often used for automating tasks by creating macros (or sub-programs). These macros can interact with the spreadsheet, internet and other Office programs. The model algorithms defined in Section 3 were written into Excel VBA by using functions and subs.

A sub is a "sub-program" code that performs a specific action or set of actions when called by another sub. A function is a program that returns a value when called. Typically, values are passed by a sub into the function in order to return a value. The program utilizes subs to control the process flow, determination of inputs, interaction between algorithms and determination of outputs. Subs use functions for algorithm calculations. This organization of code allows for quick identification and modification of algorithms within the functions without much modification to subs.

The model functions as follows: 1) user determines input variables; 2) input variables are stored in hidden spreadsheets; 3) when the program is run, the main sub is called that executes entire program based on inputs; 4) subs are used to determine specific inputs, pass them to functions and calculate the outputs; 5) once all of the outputs have been calculated, a sub is used to sort the output data and records these on a results spreadsheet visible to the user.

Inputs

The user interacts with the program through Excel userforms. A userform is a pop-up window that allows users to input information that is critical to the running of the program. The inputs in these userforms include all of the information that is fed into the algorithms developed in Section 3. In the model, inputs are categorized as either well dependent or independent. Well dependent variables include well volume information, location for wells and water quality (TDS and TSS for ZLD). Well independent variables include location of SWD and centralized plant, cost per tank, trucking cost per hour, load/unload time, truck load, treatment costs, source water cost, injection cost, pipeline cost, number of tanks, treatment recovery, lifespan, solids disposal cost and ZLD treatment cost.

When a user inputs a variable, it is stored on a hidden spreadsheet. Sets of well independent variables can be stored by the user. The database of well independent variables is a hidden set of worksheets and the name of each database is the name of the worksheet. Recall from Section 3 that volume is input as either a constant annual average or a decline curve with three parameters defining the function. The user selects which type of volume to be used and inputs the corresponding information as such. The well dependent variables of volume, latitude and longitude are contained on two separate spreadsheets: one for constant average volume and the other for decline curve volume.

Geospatial calculations

In Section 3, transportation costs could be calculated with distance (pipeline and trucking) and average truck speed (trucking). This would assume that a user knew the actual distance between locations and typical trucking speed. In order to mitigate the error from trucking input and additional work for user to calculate distance, latitude and longitude inputs can be used to geospatially calculate distance and accurate travel times.

Google provides a service called Google Maps API that allows full usage of Google Maps services by querying a serving using a URL. Given that the user computer has internet access, Excel VBA can query the internet. The program uses a sub that takes latitude and longitude inputs and calculates distance and travel time from well-to-SWD, well-to-centralized and centralized-to-SWD locations. These travel times and distances are databased and used for transportation calculations.

Google Maps API outputs in JSON (JavaScript Object Notation). In order to parse JSON outputs to a string readable by Excel VBA, an open source JSON-VBA parser was used. The VBA-JSON Copyright 2016 by Tim Hall code is available on

GitHub (https://github.com/VBA-tools/VBA-JSON) and permission of use is granted via MIT License.

Program functionality

An array is a collection of data elements. Data elements have specific types (i.e. string, integer). In Excel VBA, arrays can be constructed of elements with varying data types by using a user-defined type (UDT). This allows data structures to be constructed different corresponding types. For example, one could log well name, flow rate, latitude and longitude all in the same data structure even though the multidimensional array consists of differing data types. These UDTs were used in the programming of the model for data inputs, calculating additional inputs and recording outputs.

Recall that the user-defined inputs are recorded on hidden worksheets. In order for the program to run, the data must first be transcribed into arrays for use in the code. This simply means that arrays are built and defined, and the data points are read in off the hidden worksheets. This occurs for both the well dependent and independent variable sets. After reading in this data, the program looks to see if a volume calculation is necessary or if a constant annual average is used. If volumes must be calculated based on decline curves, it uses the input curve information to integrate between each year and calculate the total volume produced per well per year. Following the volume determination, the program uses Google Maps API to calculate distance and travel time information. Well name, volume, distance and travel time information are all written into a UDT that is used in subsequent calculations.

Once all of the inputs are recorded in their specific arrays, the program proceeds through a series of subs that uses calculation algorithms explained in Section 3. Each sub uses passes inputs into functions that return outputs. After every sub for each scenario has run, a final determination program evaluates the lowest management cost per barrel and the highest breakeven cost per barrel. All of the information is recorded on the results worksheet and is displayed to the user.