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Managing Water in the West

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Summary of Current Research on Produced Water Treatment

Research and Development Office
Science and Technology Program

U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office
Denver, Colorado

September 2016

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Water demand and water production in the oil and gas industry is significant and has the potential to impact water supplies (both positively and negatively) in the western United States (US). Many of the water treatment-related challenges currently addressed in the Bureau of Reclamation's (Reclamation) Science and Technology (S&T) Research Program and Desalination and Water Purification Research and Development (DWPR) Program are common to the oil and gas industry. This report summarizes (1) the potential impact of water produced and consumed in the oil and gas industry on Reclamation project areas, (2) past research by Reclamation and others in oil and gas water management, and (3) identifies current research thrust areas and potential for Reclamation involvement in future efforts.

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by

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Acronyms and Abbreviations

bbl	barrel
CDT	capacitive deionization
DOE	Department of Energy
DWPR	Desalination and Water Purification Research and Development
EPA	United States Environmental Protection Agency
FT	freeze-thaw
FTE®	freeze-thaw process
gal/min	gallons per minute
GIS	Geographic Information System
IPSC	Integrated Precipitative Supercritical
Interior	Department of Interior
kWh	kilowatt-hour
LLC	limited liability company
MCL	maximum contaminant level
MF	microfiltration
mg/L	milligram/liter
NETL	National Energy Technology Laboratory
NF	nanofiltration
NORM	naturally occurring radioactive materials
NPDES	National Pollutant Discharge Elimination System
NSF	National Science Foundation
PSF	polysulfone
Reclamation	Bureau of Reclamation

RO	reverse osmosis
RPSEA	Research Partnership to Secure Energy for America
S&T	Science and Technology
SAR	sodium adsorption ratio
TDS	total dissolved solids
UF	ultrafiltration
ULPRO	ultra-low pressure reverse osmosis
UOG	Unconventional Oil and Gas
US	United States
USGS	United States Geological Survey
WWTP	Waste Water Treatment Plant

Disclaimer

Executive Summary

Water demand and water production in the oil and gas industry is significant and has the potential to impact water supplies (both positively and negatively) in the western United States (US). In recent years, the demand for fresh water for hydraulic fracturing has increased dramatically in areas where fresh water supplies are constrained. The water that is generated during oil and gas extraction, termed produced water, typically has elevated levels of salts, metals, and organic constituents and is seen as a waste by-product in the oil and gas industry.

When petroleum prices are low, as they currently are, the need for better water management practices to reduce cost is more important than ever. Identifying alternative water supplies for hydraulic fracturing and recycling the flowback water are critical to ensuring water supply sustainability and satisfying competing demands for fresh water. Furthermore, with suitable treatment, fracturing flowback water and produced water can be used to augment conventional water supplies for irrigation, livestock watering, and stream flow augmentation.

Many of the water treatment-related challenges currently addressed in the Bureau of Reclamation's (Reclamation) Science and Technology (S&T) Research Program and Desalination and Water Purification Research and Development (DWPR) Program are common to the oil and gas industry. Cost, energy consumption, concentrate management, chemical use, and operational complexity are recognized challenges in both the water treatment industry and the oil and gas industry. Advances in either of these industries have the potential to positively impact the other. For example, the oil and gas industry has more tolerance for risk and economic drivers that allow the use of newer, more cutting edge technologies. These same technologies may not be cost effective for municipal water treatment. Therefore, maintaining an expertise and awareness of water treatment issues in the oil and gas industry can help Reclamation identify new technologies and solutions to technical challenges that may benefit the municipal water treatment industry.

Two areas are identified, and discussed in detail in this report, for Reclamation involvement in water management related to oil and gas:

- Treatment of produced and flowback water for beneficial use, such as irrigation and livestock water

- Treatment and use of non-traditional water as an alternative to fresh water for hydraulic fracturing

This report summarizes (1) the potential impact of water produced and consumed in the oil and gas industry on Reclamation project areas, (2) past research by Reclamation and others in oil and gas water management, and (3) identifies current research thrust areas and potential for Reclamation involvement in future efforts.

Contents

Executive Summary v
1. Introduction 1
2. Oil and Gas Industry Water Challenges in Reclamation's Service Area 3
3. Reclamation Research 5
3.1 Science and Technology Funded Research 5
3.1.1 Fouling Resistant Membrane for Produced Water Desalination (2006) 5
3.1.2 Produced Water Workshop (2006) 7
3.1.3 Beneficial Use of Produced Water (2007 to 2010) 9
3.1.4 Treatment and Beneficial Use of Produced Water (2011, 2012) ... 11
3.1.5 Produced Water Treatment Primer for Oil and Gas Operations (2013, 2014) 11
3.2 Manuals and Standards 11
3.2.1 Guidance to Evaluate Water Use and Production in the Oil and Gas Industry (2014) 12
3.3 Desalination and Water Purification Research Program 12
3.3.1 Multi-Beneficial Use of Produced Water Through High-Pressure Membrane Treatment and Capacitive Deionization Technology (2009) 12
3.3.2 Novel Fouling Resistant Membranes for Water Purification (2008) 14
3.3.3 Membrane Technology for the Recovery of Produced Water (Not published) 14
3.3.4 DWPR Projects on Technologies Used in the Oil and Gas Industry 15
3.3.4.1 Dewvaporation 15
3.3.5 Natural Freeze-Thaw Process 17
4. Research Funded by Others 17
4.1 Multi-Agency Collaboration on Unconventional Oil and Gas Research 18
4.2 Department of Energy 19
4.2.1.1 RPSEA Unconventional Resources Program 19
4.2.1.2 RPSEA Small Producers Program Relevant Projects Summary 20
4.3 National Science Foundation 20
4.4 National Laboratories 23
5. Recommendations for Future Work 23
5.1 Increasing Agricultural Water Supplies Through Treatment and Beneficial Use of Flowback and Produced Water 24

5.2 Use of Alternative Water Supplies for Hydraulic Fracturing 25
References 27

Figures

Figure 1.—Role of water in the lifecycle of well completion and development (Anon 2012). 1
Figure 2.—Potential for water treatment to improve water use efficiency during oil and gas production (Dahm & Guerra 2013b). 2
Figure 3.—Map showing oil and gas producing basins with Water2025 areas of potential water conflict (Guerra et al. 2011). 4
Figure 4.—TDS distribution of wells in the produced water database (Benko & Drewes 2008). 6
Figure 5.—Variability of produced water salt composition by basin. 7
Figure 6.—Estimated volumes of produced water generated in the western U.S. ..9
Figure 7.—Oil and gas production and acres of irrigated agriculture (Guerra et al. 2011). 10
Figure 8.—Framework for alternative water use and treatment in the oil and gas industry (Dahm 2014). 13

Tables

Table 1.—Summary of Relevant Research from RPSEA Unconventional Resources Program. 21
Table 2.—Summary of Relevant Research from RPSEA Small Producers Program 21
Table 3.—Government Labs working in oil and gas water management.............23

1. Introduction

Water is a critical part of oil and gas resource development and extraction; water is both consumed and produced at different stages of hydrocarbon production. Water is required for well completions, hydraulic fracturing, and other well stimulation techniques to increase oil and gas production. A water based solution (termed flowback water) flows back to the surface during and after the completion of hydraulic fracturing. Flowback water commonly contains clays, chemical additives, dissolved metal ions and total dissolved solids (TDS). The water usually has a murky appearance from high levels of suspended particles. Most of the flowback occurs in the first seven to ten days while the rest can occur over a three to four week time period (Schramm 2011).

Produced water is the water that exists naturally in oil and gas formations and is brought to the surface during petroleum extraction. Approximately 2 billion gallons of produced water are generated each day (Veil et al. 2004). Produced water is naturally occurring water found in shale formations that flows to the surface throughout the entire lifespan of the production well. This water has high levels of TDS and leaches out minerals from the shale including barium, calcium, iron and magnesium. It also contains dissolved hydrocarbons such as methane, ethane and propane along with naturally occurring radioactive materials (NORM) such as radium isotopes (Schramm 2011).

Many of steps in the well completion process that require water also require the transportation of water to and from the well field site, which has a significant energy requirement and environmental impact. Figure 1 shows the role of water in different phases of well completion and development.

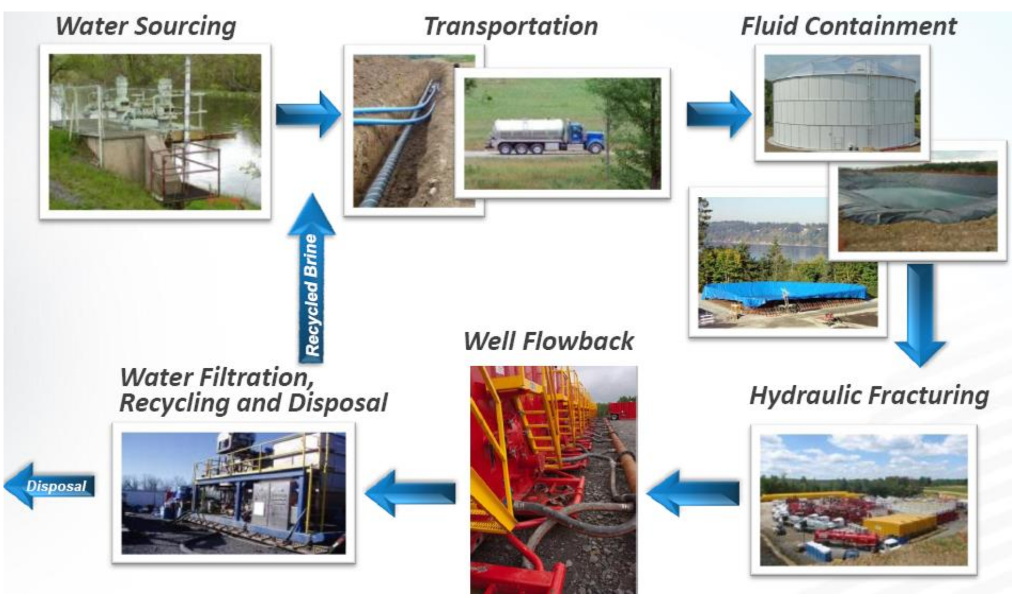

Figure 1.—Role of water in the lifecycle of well completion and development (Anon 2012).

For many years, managing, treating, and disposing of produced water in an environmentally-safe manner was the primary technical challenge for water managers in the oil and gas industry.

In the last decade, water management related to sourcing new supplies for hydraulic fracturing has become another significant challenge in the oil and gas industry. Large amounts of water are required for hydraulic fracturing, approximately 1 to 5 million gallons per well per fracturing event. Multiple wells exist on a development pad and each well can be fractured anywhere from 1 to 10 times. In many areas of oil and gas development, especially in the western United States (US), fresh water resources are already fully allocated, and sourcing fresh water for hydraulic fracturing is difficult. Treating hydraulic fracturing flowback or produced water for reuse on future fracturing jobs and for discharge back to the environment has become an important practice for water supply sustainability in the oil and gas industry.

Water treatment has the potential to both offset the water demand from the oil and gas industry and to make beneficial reuse of the water produced during oil and gas extraction. Identifying alternative sources of water for hydraulic fracturing, other than fresh water, may require treatment to make the water suitable for use. Furthermore, on-site water recycling can reduce the fresh water withdrawals needed for well completions and hydraulic fracturing. Finally, treatment of produced water can augment conventional water supplies to expand water supplies in the western US. Figure 2 shows the role water treatment can play in the oil and gas development process to both reduce water consumption within the industry and generate a useable water supply from produced water.

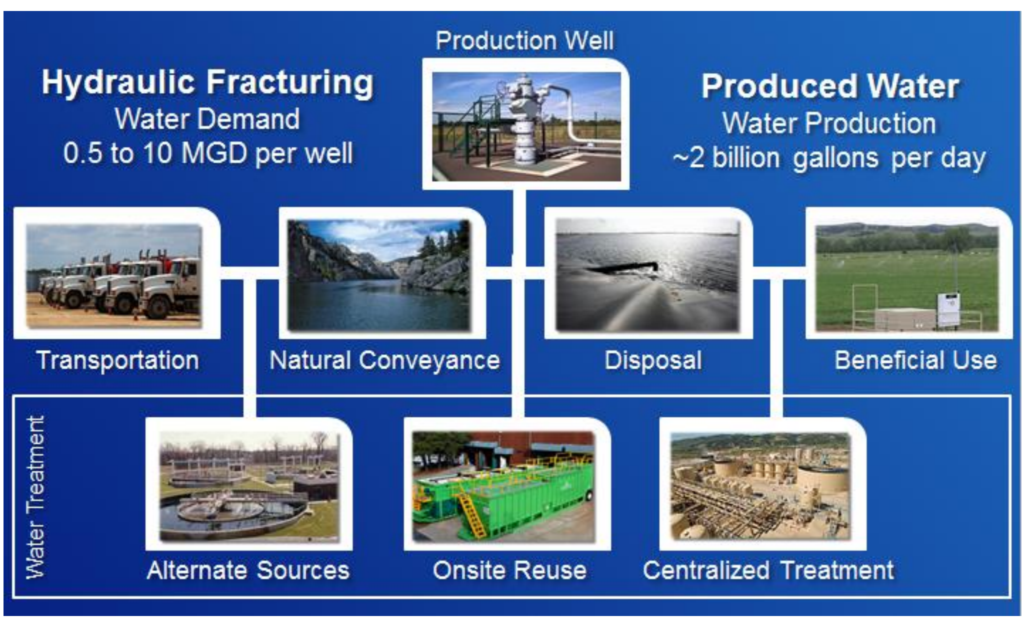

Figure 2.—Potential for water treatment to improve water use efficiency during oil and gas production (Dahm & Guerra 2013b).

Water management throughout the lifecycle of oil and gas production wells is important for water supply sustainability. Because of the large volumes of water produced and consumed by the oil and gas industry in arid regions of the western US, the Bureau of Reclamation (Reclamation) has maintained expertise and knowledge in water-related issues in the oil and gas industry. This report details past work conducted by Reclamation in produced water, current challenges in the industry, and provides recommendation for future Reclamation work in this area.

2. Oil and Gas Industry Water Challenges in Reclamation's Service Area

Approximately 80 percent of the oil and gas generated on-shore in the US occurs in the 17 western States (Veil et al. 2004). As oil and gas fields age, they tend to produce more water relative to oil and gas, therefore the amount of water produced will continue to increase as production wells age. Therein lies an opportunity for Reclamation to expand water supplies, as produced water represents an unused and non-traditional water source in the western US.

In addition to producing large amounts of brackish water, hydraulic fracturing and steam assisted gravity drainage require large amounts of water. This means that as oil and gas producers drill new wells and stimulate old wells, the demand for water in oil and gas producing areas will also increase. Many of these areas already have fully allocated fresh water resources, which means that the potential for conflict over water availability will increase. For example, according to a recent report, in Colorado and California, 97 percent and 96 percent of wells, respectively, were in regions with high or extremely high water stress. In New Mexico (NM), Utah, and Wyoming (WY) the majority of wells were in high or extremely high water stress regions. Texas, which has the highest concentration of hydraulic fracturing activity, had 52 percent of its wells in area with extremely high water stress (defined as over 80 percent of available surface and groundwater already allocated) (Freyman 2014).

The purple shaded areas in the map below (Figure 3) delineate oil and gas producing basins. The red, orange, and yellow shaded areas were identified in the Water2025 study as having a potential for conflict over water. Because of the geographical overlap between oil and gas production and areas that have limited fresh water supplies, there is a market driver for treatment and beneficial use of produced water to augment conventional supplies.

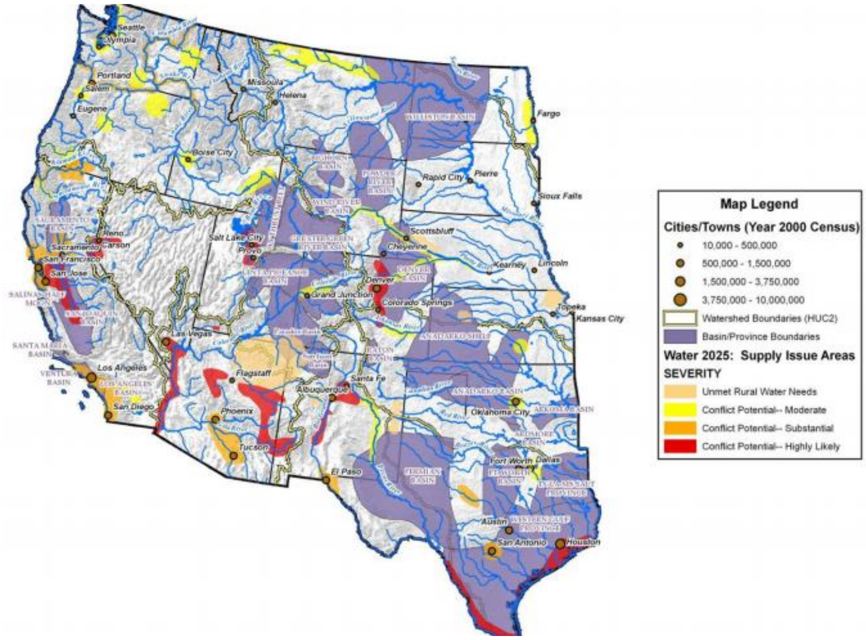

Figure 3.—Map showing oil and gas producing basins with Water2025 areas of potential water conflict (Guerra et al. 2011).

Additional drivers for collaboration between the petroleum industry and the water industry with respect to implementation of water treatment processes are:

- Reduce the cost of water treatment
- Minimize energy consumption
- Reduce chemical consumption
- Remove trace metals
- Minimize concentrate and process residuals
- Decrease system maintenance
- Reduce operational challenges associated with variable water quality and quantity
- Develop flexible, mobile, modular systems

Even though the price of oil is currently low and oil and gas production is down, there is still a need for efficient water management practices, including identifying alternative sources for hydraulic fracturing and treatment and beneficial use of produced water. Efficient water management practices enable companies to realize competitive advantages that can allow them to cost effectively produce wells that would otherwise be shut down due to water needs or excess water production.

Treatment of produced water for a valuable beneficial use can also offset water handling costs that would otherwise have been necessary. In many areas of the western US, water supplies are limited and the cost of new water rights is more expensive that treatment costs. Therefore, identifying alternative uses of produced water such as irrigation, livestock water, maintaining instream flows to allow for upstream water withdrawals can have very favorable financial implications. Therefore, even in what is considered a “low dollar environment” there is still a need for efficient water management and treatment practices in the oil and gas industry.

3. Reclamation Research

Reclamation has conducted a number of studies in produced water and water management for oil and gas. Reclamation’s work in this area has had a significant impact on the industry because Reclamation has a perspective much different from the other government agencies and private sector companies working in this field. Using a mindset of increasing water supplies and balancing competing needs for water, Reclamation has provided a unique perspective on water management to the oil and gas industry. This section describes the research activities conducted by Reclamation in this area. Research is organized by funding source.

3.1 Science and Technology (S&T) Funded Research

3.1.1 Fouling Resistant Membrane for Produced Water Desalination (2006)

This project was done in partnership with Dr. Benny Freeman’s research group at the University of Texas, Austin who received funding through the DWPR Program to develop novel, low fouling membranes for the treatment of produced water. Dr. Freeman’s research group was investigating surface modifications for ultrafiltration membranes and were testing and evaluating the integrity of the coated membrane surfaces using synthetic water sources with vegetable oil in the laboratory.

Reclamation identified the need to conduct additional testing using a testing solution that would be representative of real produced water, as a next step in the evaluation of these membranes. In the effort to identify an example of produced water quality for further testing, Reclamation conducted a significant bench top study on the geographical occurrence and composition of produced water. While not the original intent of this study, the Research and Development Office agreed that a more detailed study on produced water generation and quality was needed.

Reclamation conducted an assessment of the United States Geological Survey (USGS) database on produced water. This database has since been updated to include newer well information. The current version of the database can be found on the USGS website (Blondes et al. 2014). The original database was used to obtain a general understanding of produced water variability. The TDS for each well in the database was used to generate Figure 4 (Benko & Drewes 2008). The vast majority of wells present in the database have a TDS that is significantly higher than the secondary maximum contaminant level (MCL) for TDS for drinking water. Many of the samples showed a TDS higher than seawater. Therefore, in order for produced water to be put to beneficial, desalination is necessary.

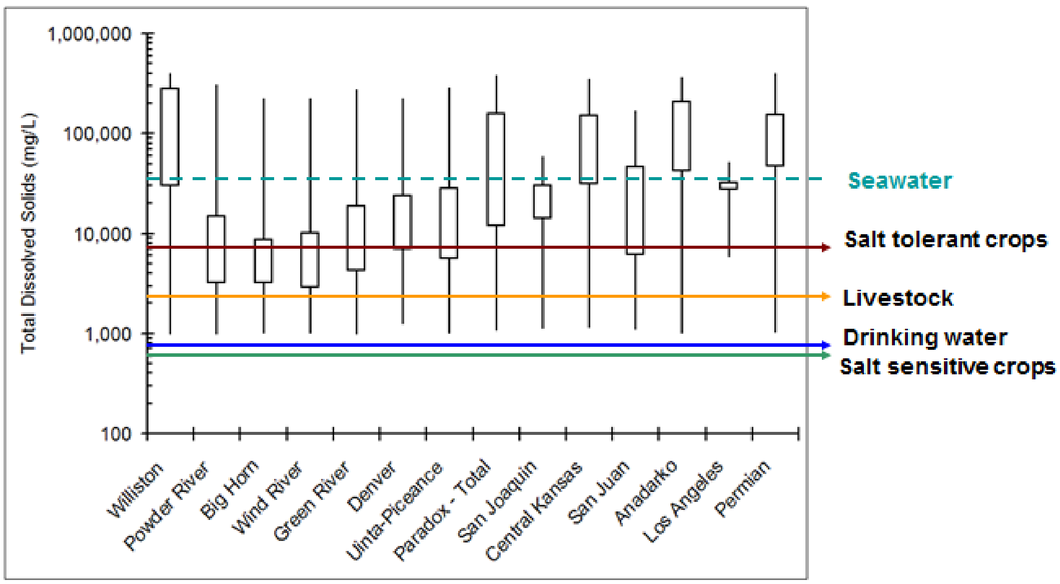

Figure 4.—TDS distribution of wells in the produced water database (Benko & Drewes 2008).

Data were available it the USGS database for the TDS concentrations and the following ions: calcium, magnesium, sulfate, and chloride. Sodium and chloride make up the majority of the ions in the produced water samples included in this database, as shown in Figure 5. The high sodium and chloride concentrations indicate that reverse osmosis would be a favorable technology for treating produced water. This work is provided in more detail in Benko and Drewes (2008).

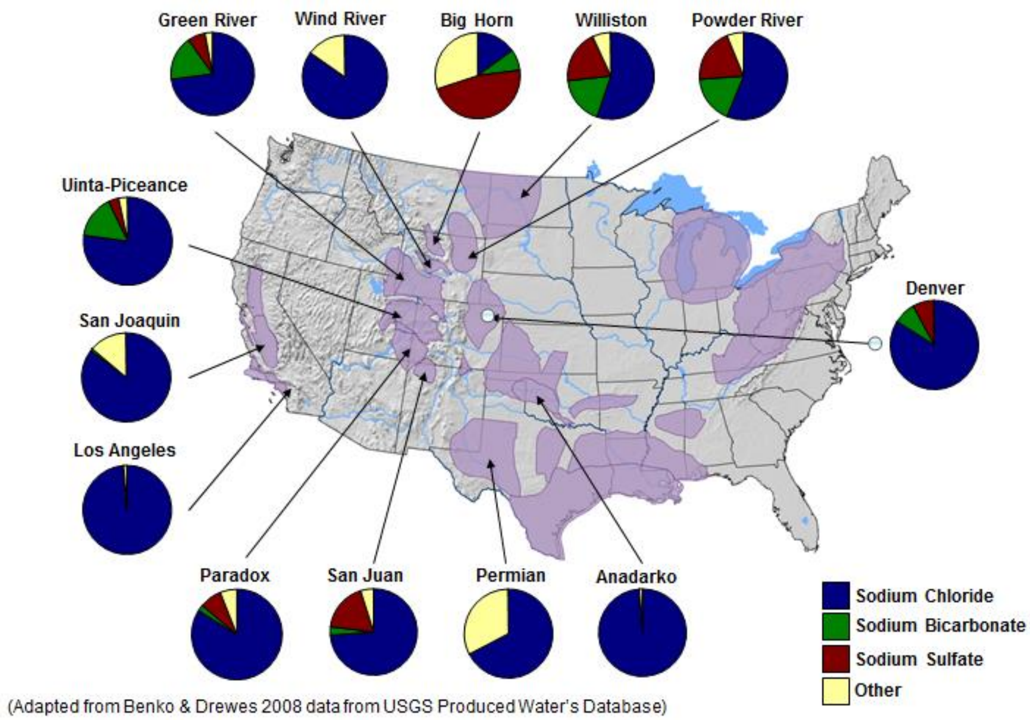

Figure 5.—Variability of produced water salt composition by basin.

3.1.2 Produced Water Workshop (2006)

The Produced Water Workshop was held in Fort Collins, Colorado, on April 4-5, 2006, to explore the potential opportunity for beneficial use of produced waters and the obstacles to making this a reality (Waskom 2006). The overriding goal of the workshop was to enhance our understanding of opportunities and challenges involved in converting produced waters to beneficial use. The workshop was attended by nearly 200 participants from government, energy companies, water users, water supply planners, government agency staff, researchers, industry representatives, and other interested parties.

The workshop did not focus on water treatment technologies because it was agreed upon that current water purification technology is generally adequate to treat produced waters where it is economically feasible. There is a portfolio of technologies available to apply depending on site-specific factors. However, final disposal of the concentrated waste from these processes is still an issue that requires further research and development.

The following conclusions were reached regarding the feasibility of treatment and beneficial use of produced water:

- The most promising opportunities to convert produced waters to beneficial use occur where produced water sources geographically align with markets for water.

- Water markets and the costs of disposal versus treatment will drive the value of produced waters and will be the fundamental factor in determining if produced waters are converted to beneficial use.

- The end users of the produced waters need to be willing to significantly offset the cost of treatment, storage, delivery, and management.

The following observations were made regarding the Federal and State role in produced water:

- States play the key role in water management and administration and must be in the lead on changing laws and policies to facilitate beneficial uses of produced waters.

- Federal agencies should provide leadership in helping to solve these problems as much of the production occurs on federal lands.

The business cultures in the energy and water industries are very different, and was a major source of discussion during the workshop. The following are key points from these discussions:

- Oil and gas producers react quickly to swings in the energy market while water suppliers are engaged in a more steady market without large swings in price, unless there is an extenuating circumstance such as drought.

- Energy companies work quickly in accessing their non-renewable supplies while raw water suppliers (generally government organizations) work over long time scales in planning new water projects.

- Energy companies often work with high risk, while water utilities/districts try to reduce risk to the lowest possible levels.

- The general approach to water management is in conflict with the longer time frame to plan and implement water projects. Planning should occur in advance of energy production on a watershed scale.

During the workshop the following research needs were identified:

- Social sciences to help remove institutional and social barriers to beneficial use of produced water.

- Understanding and managing the long-term adverse impacts to lands, ground waters, and ecosystems from produced water discharges and beneficial use.

- Pilot and demonstration projects to provide proof of concept from treatment to beneficial use of produced water in key basins.

One avenue for pursuing these research needs is for the Department of Energy's (DOE) National Energy Technology Laboratory (NETL) and Reclamation to explore joint projects. A formal interagency state and federal cross-cutting work group is needed to enhance communication among agencies and provide a point of contact for the industry. There were also suggestions of expanding the workgroup composition to include stakeholders in the oil industry and private sector.

3.1.3 Beneficial Use of Produced Water (2007 to 2010)

From 2007 to 2010, Reclamation funded work through the S&T Program to investigate the potential for treatment and beneficial use of produced water. The work was summarized in the Reclamation Desalination Series as report #157 (Guerra et al. 2011).

Reclamation gathered data from publically available sources to describe the water quality characteristics of produced water, performed an assessment of water quantity and quality in terms of geographic location (see Figure 6) and water quality criteria of potential beneficial uses, identified appropriate treatment technologies for produced water, and described practical beneficial uses of produced water.

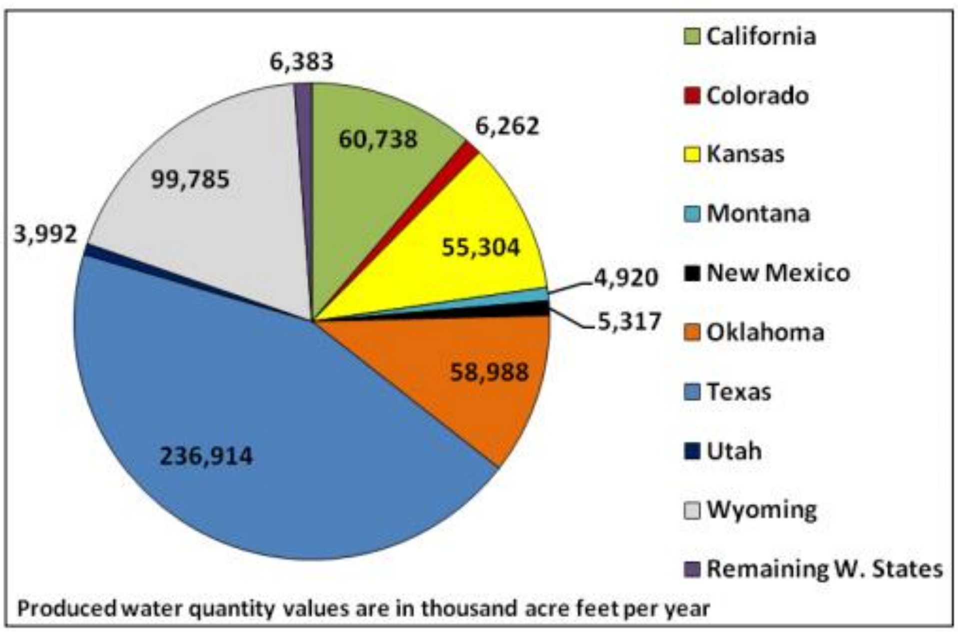

Figure 6.—Estimated volumes of produced water generated in the western U.S.

Produced water quality varies significantly based on geographical location, type of hydrocarbon produced, and the geochemistry of the producing formation. In general, the TDS concentration can range from 100 mg/L to over 400,000 mg/L. Silt and particulates, sodium, bicarbonate, and chloride are the most commonly occurring constituents in produced water. Benzene, toluene, ethylbenzene, and xylene compounds are the most commonly occurring organic contaminants in produced water.

The types of contaminants found in produced water and their concentrations have a large impact on the most appropriate type of beneficial use and the degree and cost of treatment required. Many different types of technologies can be used to treat produced water; however, the types of constituents removed by each technology and the degree of removal must be considered to identify potential treatment technologies for a given application. For some types of produced water, more than one type of treatment technology may be capable of meeting the contaminant removal target, and a set of selection criteria must be applied to narrow down multiple treatment options.

Beneficial uses of produced water include crop irrigation, livestock watering, stream flow augmentation, and municipal and industrial uses. Produced water also can be placed in aquifer storage for future use. The type of beneficial use most appropriate for a produced water application depends on the geographical location of the produced water generation, the location of the beneficial use, and the constituent concentrations in the produced water. A series of maps were produced to show the location of produced water generation in relation to areas with needs for additional water supplies. Figure 7 shows the geographic overlap between oil and gas production and areas of irrigated crops, as an example.

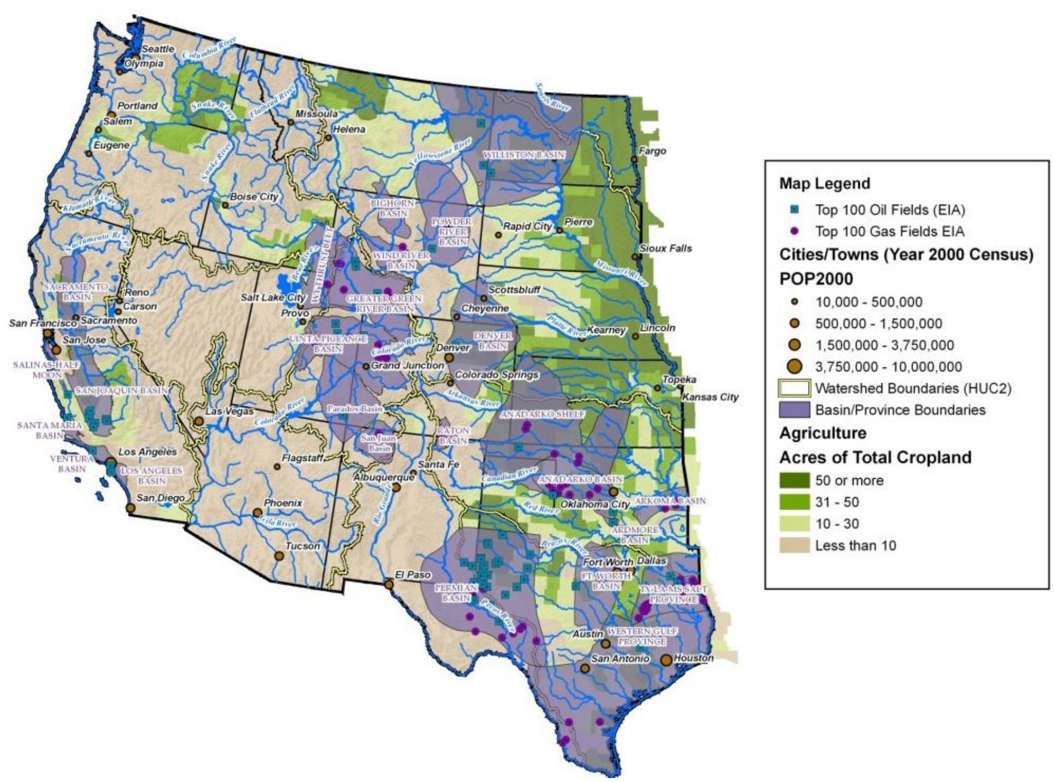

Figure 7.—Oil and gas production and acres of irrigated agriculture (Guerra et al. 2011).

Three case studies were also presented, which illustrated the large potential for beneficial use in the western US for different types of applications: agriculture, stream flow augmentation, and industrial use. Appropriate management techniques will allow produced water to be used as a resource rather than treated as a waste to meet the growing water demand in the western US.

3.1.4 Treatment and Beneficial Use of Produced Water (2011, 2012)

This project furthered the work conducted on during the 2007-2010 project. More research was conducted in collaboration with Colorado School of Mines on water quality characterization including the compilation of coalbed methane water quality data (Dahm et al. 2011). This study also proposed a method for identifying groundwater contamination from gas production using of fluorescence measurements and statistical analysis (Dahm et al. 2013). A conference presentation was given at the International Petroleum Environmental Conference summarizing the past Reclamation produced water research (Dahm & Guerra 2012).

3.1.5 Produced Water Treatment Primer for Oil and Gas Operations (2013, 2014)

This project produced a catalog of advanced water treatment technologies currently used in the oil and gas industry (Dahm & Chapman 2014). Each technology was identified as having positive and negative aspects with respect to chemical requirements, energy requirements, footprint, cost, and removal capability.

General information was included on a number of categories of applied technologies, including: a brief technology description, applicable contaminants removed, removal mechanisms, and qualitative notes on advantages and disadvantages. Links to case study examples are provided to industry information on technology applications, operational experience, and performance data.

3.2 Manuals and Standards

In 2014, Manuals and Standards funding was used to develop a guidance document for considering water use and production in the oil and gas industry for Reclamation water managers (Dahm & Guerra 2013a).

3.2.1 Guidance to Evaluate Water Use and Production in the Oil and Gas Industry (2014)

The guidance document developed in this study provides guidance to water managers on evaluating water use and production in the oil and gas sector of the energy industry (Dahm 2014). Water management strategies that highlight tradeoffs in water management options to reduce demand and increase water supply are discussed. Options highlighted include:

- Using alternative water sources to develop wells
- Providing on-site industrial water reuse or recycling
- Using produced water post-well completion in beneficial ways

This guidance includes formulas to calculate the amount of water used and produced in these various management strategies (Dahm & Guerra 2013a). This document also provides a standard assessment method for determining supply and demand with a focus on consumptive use calculations associated with energy production. A framework was developed for considering water use in the oil gas industry, shown in Figure 8.

A series of case studies were evaluated in which water treatment technologies were used to treat flowback and produced water. These case studies illustrated the technologies used and the benefits of treatment technology implementation (Dahm & Guerra 2013b).

3.3 Desalination and Water Purification Research (DWPR) Program

While the DWPR program has not had produced water treatment as a focus area, research funded through the program is applicable to the oil and gas industry. Three DWPR projects had a specific produced water focus and three others investigated technologies that have been or are currently used in use in the oil and gas industry for water treatment.

3.3.1 Multi-Beneficial Use of Produced Water Through High-Pressure Membrane Treatment and Capacitive Deionization Technology (2009)

In this study, researchers at the Colorado School of Mines investigated the use of ultra-low pressure reverse osmosis (ULPRO), nanofiltration (NF) membranes, and capacitive deionization (CDT) to treat produced water to nonpotable and potable water quality standards. Recovery of salable iodide was also investigated (Drewes et al. 2005).

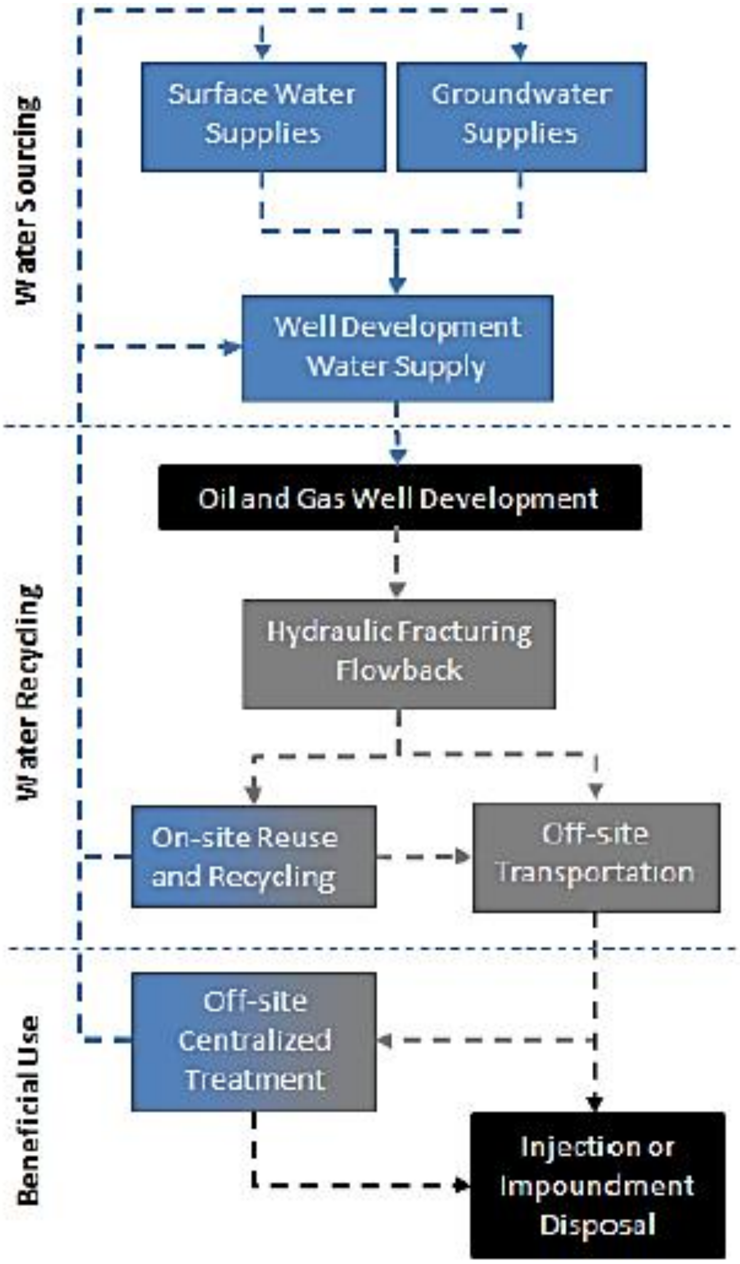

Figure 8.—Framework for alternative water use and treatment in the oil and gas industry (Dahm 2014).

Membrane fouling and scaling is the biggest challenge to employing membrane technology in produced water treatment. This study found that the fouling propensity of the membranes depended on membrane properties such as hydrophobicity and roughness. Smooth hydrophilic membranes exhibited less fouling than rough hydrophobic membranes. Chemical cleaning using caustic and anionic surfactant solutions was shown to restore permeate flux after fouling.

ULPRO membranes performed better than nanofiltration for producing high solute rejection and high recovery of iodide. ULPRO membranes were also more cost effective than nanofiltration membranes. NF membranes could be used to treat the produced water to primary and most secondary drinking water standards. Chloride and TDS exceeded the secondary standard in the NF permeate.

Compared to membrane technology, which often needs rigorous and complex pretreatment, CDT required minimum pretreatment (such as cartridge filters), and no chemicals for scaling control and chemical cleaning. However, because of slow mass transport rate of ions adsorbing onto and desorbing from carbon aerogels, water recovery for the CDT was low compared to the ULPRO process. A large amount of concentrate waste was produced during electrode regeneration and rinsing process. CDT may be a potential alternative to brackish water reverse osmosis (RO), however, the efficiency and system design need to be improved before the technology becomes economically feasible for commercialization.

Membrane technology was more cost-effective than CDT and provided a better overall performance in terms of product water quality, iodide recovery, and energy consumption. Both the product water from CDT and membrane technologies required post-treatment for stabilization, removal of boron, and adjustment of sodium adsorption ratio (SAR) for agricultural irrigation.

3.3.2 Novel Fouling Resistant Membranes for Water Purification (2008)

In this study, researchers at the University of Texas, Austin, developed an approach of applying a very thin coating of fouling-resistant polymer to membrane surfaces to increase the oil/water fouling resistance of commercially available ultrafiltration (UF), nanofiltration (NF), and RO membranes (Ju & Freeman 2006). Dynamic oil fouling filtration experiments in dead-end and crossflow modes were performed using well-characterized oil/water emulsions, and the coated polysulfone (PSF) membranes showed water flux values about five times higher than those of uncoated PSF membranes.

3.3.3 Membrane Technology for the Recovery of Produced Water (Not published)

This study, by Western Environmental, investigated microfiltration (MF), UF, NF, and RO membranes for the treatment of produced water. The study encountered challenges with testing resulting in membrane fouling and successful results were not obtained during the funding period.

3.3.4 DWPR Projects on Technologies Used in the Oil and Gas Industry

Before about 2005 the oil and gas industry was relying on the use of technologies originally developed for the municipal water treatment industry to solve its water treatment challenges. As a result, many of the technologies investigated in the DWPR program were also investigated for use in the oil and gas industry.

Typically, more novel and emerging technologies can be used economically in the oil and gas industry compared to technology use in the municipal water treatment industry. There are a number of factors that contribute to this, including:

- More favorable economic conditions
- Complex water chemistry
- Easier regulatory process for employing new technologies
- Less concern over public perception and less direct risk to public health

As a result, many emerging technologies may find commercial success in the oil and gas industry before being used for municipal purposes. In the future, technologies may be developed to the point in the oil and gas industry that they can be commercially viable for more traditional water treatment applications.

Research areas that are routinely funded by DWPR that are relevant to oil and gas water treatment include the following:

- Cost and energy reduction of treatment processes
- Concentrate management
- Zero liquid discharge
- Mineral recovery

Technologies that have been funded by DWPR that could also be applicable to the oil and gas industry include membrane distillation and forward osmosis.

The following sections describe technologies that were funded under DWPR for technology development; but weren't necessarily targeting technologies for oil and gas operations.

3.3.4.1 Dewvaporation

The DWPR program funded a pilot test of dewvaporation, a humidification-dehumidification cycle process, in 2003. In dewvaporation, feed water is evaporated by hot air on one side of a heat transfer wall and fresh water is condensed on the other side. The condensate or dew collects on the other side of the wall represents the purified water stream. Because the process uses low energy and low pressures compared to either conventional thermal and membrane processes, the operating and capital costs of the process are expected to be more favorable.

In the 2003 DWPR study (03-FC-81-0905), a 5,000-gallon-per-day dewvaporation pilot plant was designed, built, and operated at the 23rd Avenue Waste Water Treatment Plant (WWTP) in Phoenix, Arizona. The city of Phoenix Water Services Department, along with Reclamation Phoenix Area Office, cooperated to establish a pilot plant site. The pilot plant feed was the concentrate from a Tactical Water Purifier System RO unit with UF pretreatment. A 2,000 liter (mg/L) TDS waste water RO concentrate stream was treated by the pilot plant to more than 45,000 mg/L of TDS brine and 10 mg/L of TDS distillate. Recovery varied from 70 to 100 percent, with no decrease in distillate rate or increase in distillate contamination. The operating cost was estimated to be $20.85 per 1,000 gallons. The use of waste heat or solar thermal would reduce the operating cost to the cost of water pumping and air blowing. Power needs of 0.5 kilowatt-hour (kWh) per 1,000 gallons at $0.10 per kWh would amount to $0.05 per 1,000 gallons (Beckman 2008).

Since the DWPR pilot project, Altela, Inc. has licensed the technology and now sells AltelaRain® treatment plants for uses such as brine minimization in the oil and gas industry. Treatment plants range in size from 2,100 to over 10,400 gallons per day (mobile system) and larger for fixed treatment plants.

An example project installation for the AltelaRain® technology for produced water treatment is Piceance Basin Waste-To-Asset Conversion project in western Colorado (Altela n.d.). Altela partnered with a natural gas exploration company it the Piceance Basin of western Colorado to use the AltelaRain® system to treat produced water and flowback water. Altela acquired precedent-setting regulatory approvals to discharge the clean, treated water to the Colorado River Basin. This was the first of its kind non-tributary water right approval for water discharged to the Colorado River Basin for beneficial reuse.

This project is a good example of the use of water treatment technology to create a usable, valuable water supply from produced water. Other AltelaRain® projects related to water management in the oil and gas industry are installed in the San Juan Basin, NM, Marcellus Shale Basin in Pennsylvania, and in northwestern Alberta, Canada.

Another project in New Mexico, within the Navajo Nation, uses the AltelaRain® system to treat produced water generated at natural gas wells located on Navajo Nation lands. These wells were generating produced water that was being transported approximately significant distances for underground injection and disposal. By deploying the AltelaRain® system, the per gallon disposal fee was reduced by approximately 30 percent. Following treatment, the purified water was made available, for free, to the Navajo Nation for valuable re-use.

The Altela system is now also being used for the treatment of RO concentrate in the South Platte River Basin (an alternative to injection wells). The clean, treated water can be surfaced discharged to the South Platte River for valuable return flow water right credits in accordance with western prior appropriations water law frameworks. By considering water value for beneficial use such as return flows, capital outlays for additional water rights can be reduced.

3.3.5 Natural Freeze-Thaw (FT) Process

In 1998, Reclamation funded the project "Demonstration of the Natural Freeze-Thaw Process for the Desalination of Water From the Devils Lake Chain to Provide Water for the City of Devils Lake." The project took saline feed water directly from Devils Lake and desalinated it using the natural FT process. Samples of feed, treated water, and concentrated brine were collected and analyzed during operations to determine the viability of a full-scale FT plant and to demonstrate the performance of the process (Boysen & Harju 1999).

The freeze-thaw process, called FTE® process, has been operated at a commercial-scale under Wyoming Department of Environmental Quality Permits and Regulation in the Great Divide Basin of WY since 1999. The initial plant (1999-2002) had a nominal 500 barrel (bbl)/day (21,000 gallons per day) capacity. The current plant (2003 to present) has a 1,000 bbl/day capacity. The FTE® process was also operated at a commercial-scale under Wyoming Oil and Gas Conservation Commission Permits and Regulation in the Jonah Field of WY from 1997 - 2004. Pilot-scale operation of the FTE® process was successfully operated in the San Juan Basin of NM (1996 and 1997), Devils Lake in North Dakota (1999), Farson, WY (1970's) and Evers Ranch in WY (1960's and 1970's (Boysen 2008).

4. Research Funded by Others

This section describes relevant current and past research and activities conducted by others in the area of water management for oil and gas.

This section contains a summary of research funded by DOE and National Science Foundation (NSF) on produced water. There is also a summary of research conducted by the national labs and non-profit organizations. Other agencies, such as the Environmental Protection Agency (EPA) have an interest in produced water, but do not appear to be actively conducting research in this area.

Numerous private sector companies have focused on oil field services, technology vendors, and sensor and instrumentation manufacturers are also conducting a significant amount of research and pilot testing in this industry. Those activities are too numerous to summarize here, however, those companies may make very suitable partners for future work.

4.1 Multi-Agency Collaboration on Unconventional Oil and Gas Research

DOE, EPA, and the Department of Interior (Interior) formed a multi-agency collaboration to investigate research needs in the oil and gas industry. The Interior agency participating in this effort is USGS. Results of this effort were recently published in a report to the Congress (Anon 2015).

The report focused on the following topics:

- Water quality
- Water availability
- Induced seismicity
- Resource assessments
- Ecological effects
- Human health

Within the areas of water quality and water availability as they related to treatment the three agencies described their role and activities:

DOE is developing technologies for water reuse and recycling to reduce the amount of water requiring disposal or treatment. DOE is investing in technologies that could reduce the utilization of valuable freshwater resources for hydraulic fracturing. DOE conducted pilot testing of pretreatment options to allow removal of naturally occurring radioactive material, salt crystal recovery, and reuse of produced water.

DOI is researching the potential impacts of Unconventional Oil and Gas (UOG) activities on surface water and groundwater quality. Research includes determining the baseline water quality conditions; assessing the potential for migration of methane gas and other hydrocarbons; investigating the environmental contaminants due to spills from UOG wastewater management activities, and developing geochemical methods and groundwater flow models to evaluate potential contamination of water supplies.

EPA is assessing the potential impacts of hydraulic fracturing activities on drinking water resources in the US to improve understanding of the factors and drivers that may affect the frequency and severity of these impacts. EPA is also investigating water withdrawal impacts on drinking water supplies. Water withdrawals for hydraulic fracturing have the greatest potential to impact drinking water availability in areas with, or in times of, low water availability, exacerbated by drought, and over allocation of water. EPA researchers published a study that examined the impacts of water withdrawals in the Upper Susquehanna and Upper

Colorado River Basins. EPA's analysis has been focused on water quality impacts to drinking water rather than water availability.

Goals of future research in this area include the following:

- Identify alternative sources of water for UOG development to replace the use of freshwater sources.
- Increase the number of wastewater treatment options.

Future research identified is the following:

- Determine the effect of water withdrawals for UOG production on headwater streams and drinking water aquifers.
- Develop technologies and management practices for reducing fresh water demand and increasing the recycling of produced water.

4.2 Department of Energy

DOE has the most comprehensive research program in the area of produced water of any of the government agencies. DOE works with states, other government agencies and non-governmental organizations to develop tools to aid operators in meeting the environmental and economic challenges in managing produced water. The overall goal DOE research in this area is to allow for the expansion of oil and gas production, while protecting the environment and increasing the supply of water for consumers.

Produced water research is funded by DOE through the NETL which administers the Research Partnership to Secure Energy for America (RPSEA). The latest request for proposals due dates listed on the RPSEA website are for 2013. Most projects have been completed and the on-going projects have completion dates in 2016.

4.2.1.1 RPSEA Unconventional Resources Program

Under RPSEA, the Unconventional Resources Program funds work on water management, including water use planning and treatment. The mission of the Unconventional Resources Program is to increase the supply of domestic natural gas and other petroleum resources by reducing the cost and increasing the efficiency of exploration for and production of such resources, while improving safety and minimizing environmental impact (http://www.rpsea.org/ unconventional-resources-program/). Water is a critical component to meeting this program objective. A summary of relevant water treatment projects as part of the program is provided in Table 1.

4.2.1.2 RPSEA Small Producers Program Relevant Projects Summary

The Small Producer Program is established to benefit small producing companies in technology development for mature oil and gas fields, with the objective of extending the life and ultimate recovery of these fields. This is an important group to overall US production. The goal of this program is to carry out research, development and demonstration efforts that will assist small producers in reducing the cost and increasing the efficiency of exploration and production while operating safely and in a manner which does not harm the environment. Efficient, cost effective water management is a critical part of achieving that objective. A summary of relevant water treatment projects as part of the program is provided in Table 2.

4.3 National Science Foundation

The National Science Foundation (NSF) has funded research in the area of produced water treatment through the Small Business Innovation Research program. Through this program, NSF has funded small business to develop new technologies for treating produced water. Absorbent Materials Company, received a Phase I and Phase II award to investigate the use of swellable glass absorbents for the removal of organic compounds from produced water. Symbios Technologies also received an award to develop a technology to develop a plasma treatment system to oxidize organic compounds for treatment of waters such as produced water.

FloDesign Sonics developed a new, efficient separation technology to treat produced water. The process uses a method called acoustophoresis, in which droplets or particles within a liquid can be manipulated with a special acoustic wave pattern. Depending on their relative density compared to the liquid, these larger clusters either settle to the bottom or rise to the surface, where they can be separated easily. The technology can remove particles smaller than 20 microns without the addition of chemicals. The company has 7,000 -gallon per day prototype for pilot testing with plans to develop a 100,000 gallons per day system.

NSF is currently funded the Air Water Gas Network, Routes to Sustainability for Natural Gas Development, and Water and Air Resources in the Rocky Mountain Region, a Sustainability Research Network. Water treatment is a component of this larger, multi-disciplinary effort. The water treatment team members are working to develop sustainable techniques for on-site treatment of wastewater that could decrease the need for trucking and injecting wastewater into deep wells, and increase the feasibility of water re-use, including forward osmosis and membrane distillation.

Table 1.—Summary of Relevant Research from RPSEA Unconventional Resources Program.

Project Title	Conducting Organization	End Date	Brief Description
An Integrated Framework for the Treatment and Management of Produced Water	Colorado School of Mines	2011	This project developed a web-based treatment selection and screening tool that allow for the selection of the best fit for purpose technology for treating produced water from coalbed methane extraction.
Pretreatment and Water Management for Fracturing Water Reuse and Salt Production	General Electric Global Research	2011	This study investigated a lime-soda process for the removal of magnesium, calcium, and strontium for nonhazardous solid waste disposal followed by barium and radium precipitation as carbonates. The carbonates were re-dissolved and disposed of by well through the Underground Injection Control program. A second process was studied that used manganese dioxide as an adsorbent for barium and radium.
Novel Engineered Osmosis Technology: A Comprehensive Approach to the Treatment and Reuse of Produced Water and Drilling Wastewater	Colorado School of Mines	May 2016	The objective of this research effort is to investigate the osmotically driven membrane processes. The proposed research will advance the development and implementation of the forward osmosis, osmotic dilution, and a novel ultrafiltration processes for treatment and management of well drilling and stimulation wastewater and produced water in many unconventional and conventional gas and oil fields.
Advancing a Web-Based Tool for Unconventional Natural Gas Development with Focus on Flowback and Produced Water Characterization, Treatment and Beneficial Use	Colorado School of Mines	May 2016	The objective of this study is to provide a set of web-based tools that will enable producers and other users to characterize, treat, beneficially use, and manage produced water and fracturing flowback water from unconventional gas production. The goal is to sustain gas production while minimizing potential impacts on natural water resources, public health, and environment. Built upon the integrated decision making framework developed for CBM produced water management, the proposed study focuses on shale gas and tight sand production, the most difficult and least developed.
Development of Geographic Information System (GIS)-Based Tools for Optimized Fluid Management in Shale Gas Operations	Colorado State University	Sept 2016	The overall objective of the proposal is to develop GIS-based tools that can be used to optimize water management decisions during unconventional oil and gas development and production to minimize the environmental impact. The environmental impacts that will be directly assessed with the tool include the handling, treatment and disposal of produced water, air toxics and greenhouse gases associated with fluids handling, water footprint, and the optimal siting of wells and treatment facilities with respect to community impacts.
Advanced Treatment of Shale Gas Fracturing Water to Produce National Pollutant Discharge Elimination Program Quality Water	M2 Water Treatment	2015	The project will investigate an integrated approach using magnetic ballast clarification , vortex-generating,and NF membranes, and hydrogel media or precipitation/solidification/stabilization to treat produced water
Cost-Effective Treatment of Flowback and Produced Waters Via an Integrated Precipitative Supercritical (IPSC) Process	The University of Ohio	2015	A treatment process consisting of ultraviolet treatment, chemical precipitation/adsorption, and supercritical water was constructed and tested to validate technical feasibility and to acquire information necessary to design, construct, and operate a pilot-scale IPSC process unit. In the second phase of the project, performance of a pilot-scale IPSC process unit will be demonstrated in order to acquire engineering information necessary to develop detailed techno-economic evaluation and a commercial-scale engineering design package.

Table 2.—Summary of Relevant Research from RPSEA Small Producers Program

Project Title	Conducting Organization	End Date	Brief Description
Cost Effective Treatment of Produced Water Using Co-Produced Energy Sources for Small Producers	New Mexico Institute of Mining and Technology	2012	This project aimed to demonstrate a cost-effective process for produced water purification at the wellhead using a low-temperature distillation unit (humidification/dehumidification process). The researchers constructed a demonstration unit that can utilized solar energy and coproduced geothermal energy for wellhead produced water desalination (http://www.rpsea.org/projects/07123-05/).
Cost Effective Treatment of Produced Water Using Co-Produced Energy Sources, Phase II: Field Scale Demonstration and Commercialization	New Mexico Institute of Mining and Technology	2015	This project continued the development of the humidification/dehumidification process. The process was shown to use solar energy and other co-produced energy sources to reduce the electricity consumption of the process to 0.16 kWh/barrel resulting in a water production cost of approximately $0.18/barrel (http://www.rpsea.org/media/files/project/08495dd0/11123-03-TS-Cost-Effective_Treatment_Produced_Water_Co-Produced_Energy_Sources-12-14-12.pdf).
Treatment and Beneficial Reuse of Produced Waters Using a Novel Pervaporation-Based Irrigation Technology	University of Wyoming	2014	The project evaluated the application of a novel pervaporation-based irrigation technology to treat and reuse oil and natural gas produced water. The project found that pervaporation process showed promise to be used as a treatment and irrigation system. However, for treating the volumes of produced water generated using this technology for irrigation the membrane properties would need to be improved (http://www.rpsea.org/media/files/project/60b022ec/09123-11-FR-Treatment_Beneficial_Reuse_Produced_Waters_Novel_Pervaporation_Irrigation-03-20-14_P.pdf).
Basin-Scale Produced Water Management Tools and Options – GIS-Based Models and Statistical Analysis of Shale Gas/Tight Sand Reservoirs and Their Produced Water Streams	Utah Geological Survey	2015	This project had the following objectives: (1) create basin-wide, digital produced water management tools that integrate produced water character, water disposal/reuse, water transport, and groundwater sensitivity factors to allow for quicker and more efficient regulatory and management decisions related to unconventional gas developments in the Uinta Basin; (2) investigate the option of beneficial use of produced water treatment for geothermal heat recovery or power generation in the Uinta Basin; (3) promote maximized produced water reuse which will minimize use of freshwater in unconventional gas development and production; (4) compile Uinta Basin produced water management practices and recommend best practices; and (5) seek to increase protection of critical Uinta Basin alluvial aquifers.
A Portable, Two Stage, Antifouling Hollow Fiber Membrane Nanofiltration Process for the Cost Effective Treatment of Produced Water	New Mexico Institute of Mining and Technology	June 2016	The overall objective of this project is to develop and demonstrate the performance and cost-effectiveness of the portable Two-Stage, Antifouling Hollow Fiber Membrane NF process to convert produced water into a clean water product for a reused fluid or direct discharge.
Water Treatment System for Effective Acid Mine Drainage Water Using Hydraulic Fracturing	PPG Industries	July 2016	The project will develop a novel ion exchange membrane and water treatment process capable of reducing sulfates to no more than 500 ppm at bench-scale influent flow rates of 1-5 gal/min. Filter cartridges, skids, and system maintenance processes for the new system will be evaluated at intermediate scale influent flow rates of 10-50 gal/min. This design will be optimized so that one, non-specialized laborer can operate and maintain the system. This design will undergo field validation of the efficacy and ease of use of the new treatment process. The field tests will be conducted at drilling locations at targeted influent flow rates of 400-500 gal/min.

4.4 National Laboratories

National laboratories have conducted research in the area of produced water. The following table summarizes efforts by the labs, Table 3.

Table 3.—Government Labs Working In Oil and Gas Water Management

Agency	Summary of Research
Los Alamos National Laboratory	Developing novel technologies to treat produced water as new water source in NM, beneficial use of produced water for growing biofuel precursors
National Renewable Energy Laboratory	Investigating the use of water treatment technologies to increase energy and water supplies in a cost effective manner
National Energy Technology Laboratory	Administers DOE program on produced water, studied constructed wetland treatment systems for produced water
Argonne National Laboratory	Investigate water quality, quantity and identify treatment options for produced water. Produced White Water Paper: background and regulations on produced water as well as discussion on options for managing produced water (prepared for the DOE)
Sandia National Laboratory	Conduct applied research projects in desalination of brackish ground waters and produced waters Developed “Energy-Water Decision Support System” to enable planners to analyze the potential implications of water stress for transmission and resource planning

5. Recommendations for Future Work

Based on the past research by Reclamation and the research currently being conducted by others, recommendations are made for future work in this area. Future efforts by Reclamation should focus on partnering with others working in this area in order to make a meaningful contribution to solving Reclamation’s water supply challenges as well as improving water challenges in the oil and gas industry.

Two potential areas are identified for future work. These two potential projects are based on the premise of efficient water management and treatment of non-traditional water sources to increase water supplies for stakeholders with competing needs for water.

5.1 Increasing Agricultural Water Supplies Through Treatment and Beneficial Use of Flowback and Produced Water

A promising area for Reclamation involvement in oil and gas water management is the study of agricultural uses for fracturing flowback water and produced water. Due to public perception challenges associated with these water sources, the use of produced and flowback water for drinking is unlikely; however, there is a potential for produced water to be treated and used for irrigation and livestock watering. The use of flowback and produced water to offset conventional supplies currently used for irrigation would free up more water because standards for irrigation water are much lower than drinking water standards for other uses and may increase water usage efficiency.

Because the management of flowback and produced water typically requires disposal costs such as transportation and treatment, the treatment of these waters for agricultural purposes may be almost entirely offset by the disposal costs paid by the industry. Therefore, there is a huge potential for flowback and produced water to be treated for agricultural water affordably.

Based on the past research in produced water, it is clear that in order to make an impact, projects need to be multi-disciplinary and actively involve project partners and stakeholders. The beneficial use of produced water is multi-faceted and would require the successful, engagement of stakeholders and partners. Potential partners for a project in this area include the following:

- Irrigation district(s) in states with significant oil and gas development, such as Texas, California, Oklahoma, Colorado, or the Dakotas
- Relevant Reclamation area office
- Well field service companies and petroleum producers
- Treatment equipment suppliers

The project would include the selection of a relevant, representative study area. Selection of the study location should consider the type of petroleum produced, production water needs, and water production characteristics.

Water quality requirements for agricultural uses such as irrigation and livestock watering should be identified and characterized. The produced water and flowback water quality can be compared to the water quality requirements of the beneficial uses to determine treatment needs.

Institutional and regulatory issues will need to be considered to understand the implications of augmenting agricultural water supplies on water rights in the area.

This will help to determine how produced water can be used to offset current agricultural water uses in the area. A framework will be developed that can be used as a model for implementation in other areas.

Pilot testing of the treatment technology is necessary to understand the cost of the water produced as this will be a critical determining factor in the feasibility of the use of produced water.

5.2 Use of Alternative Water Supplies for Hydraulic Fracturing

The use of alternative water (such as brackish groundwater or treated wastewater) rather than conventional supplies for oilfield uses (such as hydraulic fracturing, drilling fluids, and other field water uses) is an area where Reclamation's water resources experiences, knowledge of local stakeholders needs and concerns, and water treatment experience could be leveraged to reduce the competing needs for fresh water resources in Reclamation project areas with oil and gas development. Potential partners for this project include:

- Well service companies and petroleum producers
- Local Reclamation area office

As in the previous project, the selection of the project focus area is critical and should be selected to include an area with a projected increase in the use of hydraulic fracturing. Areas to consider include those currently experiencing water stress due to increasing fresh water demand, changing water availability due to drought and climate change, and a include a diverse array of water users.

References

Altela, http://altelainc.com/.

Anon, 2012. Anadarko Petroleum. In *2nd Annual Shale Gas Water Management Conference*.

Anon, 2015. *Report on the Multi-Agency Collaboration on Unconventional Oil and Gas Research*, Washington DC. Available at: http://unconventional.energy.gov/pdf/MAC_2015_Report_to_Congress_sign.pdf.

Beckman, J.R., 2008. *Dewvaporation Desalination 5,000-Gallon-Per-Day Pilot Plant*, Denver.

Benko, K. & Drewes, J.E., 2008. Produced Water in the Western United States: Geographical Distribution, Occurrence, and Composition. *Environmental Engineering Science*, 25(2).

Blondes, M.S. et al., 2014. U.S. Geological Survey National Produced Waters Geochemical Database v2.1 (PROVISIONAL). *Energy Resources Program - Produced Waters*. Available at: http://energy.usgs.gov/Environmental Aspects/EnvironmentalAspectsofEnergyProductionandUse/ProducedWaters.aspx#3822349-data.

Boysen, J., 2008. The Freeze-Thaw/Evaporation (FTE(r)) Process. In *International Petroleum Environmental Conference*.

Boysen, J.E. & Harju, J.A., 1999. *Evaluation of the natural freeze-thaw process for the desalination of groundwater from the North Dakota aquifer to provide drinking water for Grand Forks, North Dakota*, Denver.

Dahm, K., 2014. *Guidance to evaluate water use and production in the oil and gas industry*, Denver.

Dahm, K. & Chapman, M., 2014. *Produced Water Treatment Primer: Case Studies of Treatment Applications*, Denver.

Dahm, K. & Guerra, K., 2013a. Guidance for the evaluation of produced water as an alternative water supply. In Denver, ed. *AWWA Sustainable Water Management Conference*.

Dahm, K. & Guerra, K., 2013b. Produced Water Case Studies. In *EUCI: Produced Water Management in the West*.

Dahm, K. & Guerra, K., 2012. Produced Water Management for Oil and Gas Operations. In *19th Annual International Petroleum Environmental Conference*.

Dahm, K.G. et al., 2011. Composite Geochemical Database for Coalbed Methane Produced Water Quality in the Rocky Mountain Region. *Environmental Science & Technology*, 45(18), pp.7655–7663. Available at: http://dx.doi.org/10.1021/es201021n.

Dahm, K.G. et al., 2013. Identifying Well Contamination through the use of 3-D Fluorescence Spectroscopy to Classify Coalbed Methane Produced Water. *Environmental Science & Technology*, 47(1), pp.649–656. Available at: http://dx.doi.org/10.1021/es303866k.

Drewes, J.E. et al., 2005. *Multibeneficial Use of Produced Water Through High-Pressure Membrane Treatment and Capacitive Deionization Technology*, Denver.

Freyman, M., 2014. *Hydraulic Fracturing and Water Stress: Water Demand by the Numbers*, Boston. Available at: http://www.ceres.org/resources/reports/hydraulic-fracturing-water-stress-water-demand-by-the-numbers.

Guerra, K., Dahm, K. & Dundorf, S., 2011. *Oil and Gas Produced Water Management and Beneficial Use in the Western United States*, Denver.

Ju, H. & Freeman, B.D., 2006. *Novel Fouling-Resistant Membranes for Water Purification*, Denver.

Schramm, E., 2011. What is flowback, and how does it differ from produced water? *The Institute for Energy & Environmental Research*.

Veil, J. et al., 2004. *A White Paper Describing Produced Water from Production of Crude Oil, Natural Gas, and Coal Bed Methane*,

Waskom, R., 2006. *Produced Waters Workshop*, Fort Collins, CO: Colorado Water Resources Research Institute. Available at: http://www.cwi.colostate.edu/publications/is/102.pdf.