GROUNDWATER PROTECTION COUNCIL

PRODUCED WATER REPORT

Regulations, Current Practices, and Research Needs

Acknowledgements

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Dear Reader:

I would like to express my deep appreciation to all the people who contributed to the Produced Water Report. I especially want to thank those who served on the leadership team for their dedication and effort in bringing the report to fruition. To produce a balanced report, we engaged geologists, engineers, lawyers, toxicologists, soil experts, public health experts, the petroleum industry, and state regulators, from whom we sought ideas and advice on the report development and conclusions. Researching facts, reviewing thousands of papers and studies, conducting dozens of meetings, writing, editing and final production — all required a myriad of experts on a variety of critical topics.

This report is a seminal work about produced water regulation and reuse. It contains the most current information available about regulatory frameworks, produced water use in oil and gas operations, and potential future uses of produced water outside of oil and gas operations.

While we believe the report is exhaustive, it is by no means the final word with respect to produced water reuse. We expect future efforts to continue developing a more mature understanding of produced water characteristics and reuse potential. We trust that our report will provide a solid base of reference for these efforts.

We are grateful for the funding provided by several organizations including the U.S. Department of Energy, Ground Water Research and Education Foundation, Environmental Defense Fund and American Petroleum Institute.

Mike Paque
Executive Director
GWPC

Preface

The Ground Water Protection Council (GWPC) is the national association of state groundwater protection and underground injection control agencies. GWPC has served as a valuable forum for communication on oil and gas issues between state government, federal government, industry, academia, environmental advocacy groups, and other interested parties. The mission of the GWPC addresses "the protection of groundwater resources for all beneficial uses." It covers all groundwater resources that are or may be used for beneficial purposes, including oil and gas produced water.

This report is part of an effort by the GWPC to promote consideration of appropriate beneficial reuses of produced water. While produced water is currently being used in applications both within and outside of oil and gas operations, many potential applications remain. Further research will be needed to assure that these potential applications are both suitable and safe.

As a direct byproduct of oil and gas production, produced water is a natural area of interest for GWPC, which places a strong emphasis on energy and water interactions. The process of regulation of underground injection of fluids (the Safe Drinking Water Act's Underground Injection Control or UIC program) is one of GWPC's major programmatic concerns.

Given its longstanding working relationship with federal agencies including the Environmental Protection Agency and Department of Energy, as well as with industry stakeholders and non-governmental organizations, GWPC is uniquely positioned to explore the current and future beneficial reuse of produced water. Recognizing that produced water has the potential to be an important contributor to water resources in the United States, the GWPC brought together scientists, regulatory officials, members of academia, the oil and gas industry, and environmental groups to explore roles produced water might play in developing greater water certainty. Their research has been synthesized in this report, which is designed to support policy makers, regulators, and the public in making informed decisions, driving additional research, and analyzing practical opportunities and challenges of beneficially reusing produced water.

This report considers produced water to be a "potential resource" rather than a "waste." Although most produced water has never had any use before it is brought to the surface, the term "reuse" is commonly assigned to produced water that is or will be used for a beneficial purpose.

This report consists of three modules.

Module 1: Current Legal, Regulatory, and Operational Frameworks of Produced Water Management. This module focuses on the multifaceted regulation of produced water, including long established federal laws and programs as well as areas where additional regulatory clarity may be needed to further advance the beneficial use or reuse of produced water. It also discusses the legal and operational aspects of produced water reuse such as ownership, water rights, liability, and standard practices. These topics define the framework under which produced water reuse may be accomplished and the challenges limiting its current implementation as a water source.

Module 2: Produced Water Reuse in Unconventional Oil and Gas Operations. This module presents information on how produced water is used within oil and gas operations, with a focus on unconventional operations. Through literature reviews, interviews with oil and gas companies, and data requests, information has been gathered on the current state of oil and gas operational reuse of produced water and on future potential reuse options and dynamics.

Module 3: Produced Water Reuse and Research Needs Outside Oil and Gas Operations. The most forward-looking part of this report, this module looks at current and needed research to properly and safely use produced water in applications outside oil and gas operations. It also discusses the range of reuse options currently available along with potential reuse options that may one day become practical.

The GWPC hopes readers will find this report informative and useful. It offers a realistic assessment of the contribution produced water could make to the national water resource portfolio and state water planning efforts. This report offers a solid base for building upon and improving the knowledge and use of produced water. It is expected that ever-changing technology and statutory transformations will only further the use of produced water in the future.

Leadership in Addressing Oil and Gas Water Management

The Ground Water Protection Council has taken the lead role in oil and gas water management issues during recent years. Examples include:

- Creating the highly acclaimed Risk Based Data Management System (RBDMS), used by more than 24 state agencies to track oil and gas data
- Implementing the FracFocus system with its unique hydraulic fracturing chemical disclosure registry, developed in collaboration with the Interstate Oil and Gas Compact Commission (IOGCC)
- Conducting several annual national conferences on energy/water interactions
- Publishing the groundbreaking primer *Modern Shale Gas Development in the United States* (April 2009), prepared in conjunction with ALL Consulting for the U.S. Department of Energy and National Energy Technology Laboratory
- Organizing the first-of-its-kind national conference on stray gas issues in 2012
- Initiating discussions on induced seismicity related to hydraulic fracturing and disposal wells in 2013, leading to formation of an induced seismicity work group and publishing of the 2015 and updated 2017 primer on *Technical and Regulatory Considerations Informing Risk Management and Mitigation*
- Sponsoring a 2015 report on national produced water volumes and management practices.

For more information on these and other efforts, see the Groundwater Protection Council website at www.gwpc.org.

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Executive Summary

Water is closely intertwined with oil and gas production, including **sourced water** (water supplied to support operations) and **produced water** (formation water brought to the surface during well completion and oil and gas production). Determining how to find sourced water and manage produced water efficiently and cost effectively is an important component of producing oil and gas. Produced water can be managed within an individual lease area or over a larger field that incorporates many wells and leases and extends over more than one county, river basin, or state.

In a 2015 Ground Water Protection Council (GWPC) report, which analyzed 2012 data, about 45 percent of produced water was used within conventional oil and gas enhanced recovery operations, leaving about 55 percent to be disposed of in permitted underground injection control (UIC) wells with a small percentage managed in other ways including evaporation and discharge.

Produced water varies widely in quality. Most produced water is highly saline and may contain a mix of mineral salts; organic compounds; hydrocarbons, organic acids, waxes, and oils; inorganic metals and other inorganic constituents; naturally-occurring radioactive material; chemical additives; and other constituents and byproducts.

GWPC recognizes that, as fresh water resources become more constrained, the ability to use produced water to offset freshwater demands both inside and outside of oil and gas operations will offer opportunities and challenges. This report is part of an effort by the GWPC to work with a variety of stakeholders to identify those opportunities and challenges and provide suggestions that policy makers, researchers, regulators, and others can use to address them. To that end, the report focuses on three key areas:

- Regulatory and legal frameworks for produced water reuse
- Current and future potential for produced water reuse in unconventional oil and gas production
- Opportunities and research needs for future reuse of produced water for purposes outside of the oil and gas industry

About This Report

This report addresses the drivers and potential benefits for increasing produced water reuse both in unconventional oil and gas operations and outside the industry, as well as complex economic, scientific, regulatory, and policy considerations, specifically with respect to risk management. It also identifies research that will be needed to enable informed decision-making on produced water reuse, as well as regulatory and policy initiatives that would facilitate reuse.

An overriding theme of this report is that opportunities for increased produced water reuse will vary greatly depending on:

- **Local conditions**, including the quality and quantity of produced water available, the profile of regional water supply and demand, geological and demographic characteristics, the cost and availability of permitted UIC disposal, and the existence or lack of infrastructure for transporting, storing, and treating produced water; and
- **The envisioned end-use scenario** and specific cost, environmental, operational, policy, regulatory, and public perception considerations, especially the level of treatment required to make the produced water suitable for the intended end use, or "fit for purpose."

Reflecting the paramount importance of local considerations and a "fit-for-purpose" approach, this report includes:

- **Profiles of the top seven basins/regions based on oil and gas production and current unconventional drilling activity:** the Permian, Appalachian, Bakken, Niobrara/ Denver-Julesburg (DJ), Oklahoma, Haynesville, and Eagle Ford basins/regions.

- **Data on water management from 18 producing companies**, with operations summarized for these seven major unconventional regions.
- **A summary — developed with the Louisiana State University School of Law —evaluating how selected states regulate produced water**, focusing on differing regulatory frameworks for produced water management, agencies responsible for regulating these processes, and produced water ownership and liability.
- **A four-phase conceptual research framework designed to assist decision-makers in assessing and reducing risks associated with a given reuse scenario where produced water is considered for uses outside of oil and gas operations**, incorporating the traditional concepts of risk-based decision-making — research, risk assessment, and risk management — as applied to produced water treatment and reuse.
- **An overview of various treatment technologies** that exist or are being actively researched today within academic, governmental, and industrial arenas.
- **A literature review** identifying hundreds of published, peer-reviewed studies and referencing other reports, which may be relevant to assessing produced water reuse or identifying knowledge gaps and current limitations.

Opportunities and Challenges

Increasing produced water reuse holds promise for making available a substantial volume of water that could potentially offset, or supplement, fresh water demands in some areas. Reuse also can be beneficial to oil and gas producers as an alternative to disposal in UIC wells, which can be costly, locally unavailable, or subject to volume restrictions. States and regulators may want to investigate reuse for reasons ranging from drought and groundwater depletion to disposal-related induced seismicity.

For the end user, in addition to considerations related to the quality of treated produced water, the economic attractiveness of reuse depends on whether the supply of produced water is predictable, whether it can be delivered reliably to the point of use, and how the cost compares to other available sources of water after factoring in the costs of its treatment and transportation as well as the disposal of treatment residuals. If local water supplies of fresh water are adequate or abundant, there is less incentive to consider beneficial reuse of treated produced water, especially given its potential associated risks.

Reuse in Unconventional Oil and Gas Operations

The multi-stage hydraulic fracturing of a single horizontal well can use an average of about 12 million gallons of water. Growth in the volumes of sourced and produced water required in hydraulic fracturing operations has raised sustainability concerns in unconventional regions, prompting greater emphasis on long-term water planning. In regions where either source water or disposal capacities are limited, produced water reuse may become economically viable and operationally practical. The area where reuse is highest, Pennsylvania and West Virginia (Appalachia), and the area where reuse is growing fastest, West Texas and New Mexico (Permian), are regions where disposal options have been or may become limited and disposal costs have been high or are increasing. In addition, several of the top basins are in arid regions with limited availability of sourced water.

Water treatment requirements for reusing produced water in hydraulic fracturing are far less demanding than for uses outside the industry. Advances in hydraulic fracturing chemistry allow operators to use produced water with minimal treatment, addressing only a few specific constituents to create “clean brine.” The approach is significantly less costly than more advanced treatment regimes such as those necessary to remove salts. However, in limited cases, advanced treatment is still done to provide an option that could meet discharge water quality requirements or reduce the potential risk from a spill.

The high costs of transporting and storing produced water, particularly in areas lacking an established water pipeline infrastructure, remain a barrier to reuse in most regions. Achieving significant levels of produced water use in unconventional producing regions will require capital investment in storage, transportation, and treatment capacity; a predictable supply of produced water; ongoing demand for source water for nearby production operations; and a supportive regulatory framework. Managing environmental risk related to transporting and storing produced water for reuse requires minimizing and remediating spills and leaks, managing residuals, controlling air emissions, and taking actions to protect wildlife. These considerations must be paramount in production operations, as well as in the design and construction of storage impoundments or tanks and permanent or temporary pipelines.

The recent emergence of water midstream solutions (coordinating water sourcing for completion operations with produced water reuse across multiple producing companies) holds promise for smoothing out the peaks and valleys of individual company water demands, reducing transportation and disposal, and reducing demands on infrastructure through shared use. The scale of water midstream could allow reuse to grow steadily, especially in the most active areas in the Permian, Appalachia, and Oklahoma.

Reuse Outside the Oil and Gas Industry

Potential options for treatment and reuse of produced water outside the oil and gas industry include land application (e.g., irrigation, roadspreading), introduction to water bodies (e.g., discharges to surface water, injection or infiltration to ground water) and industrial uses (e.g., industrial feed streams, product or mineral mining). While some options, such as surface water discharge, are in limited use today, most remain theoretical.

Currently, the feasibility of reuse is significantly greater in unconventional oil and gas operations than in applications outside the oil and gas industry, where the costs of transporting and storing produced water and, particularly, of treating it to a "fit for purpose" level can be limiting. Potential risks to health and the environment must be well understood and appropriately managed in order to prevent unintended consequences of reuse. Produced water is complex, and in most cases further research and analysis is needed to better understand and define the "fit for purpose" quality goals for treatment and permitting programs. Environmental considerations beyond direct health or ecosystem impacts include emissions from treatment, managing waste materials from treatment, cumulative ecosystem impacts, or other localized issues.

Overview of Research Needs

Most research needs identified for this report pertain to produced water treatment and reuse outside the oil and gas industry. Managing potential risks with such applications requires improved understanding of the composition of a specific produced water source and identification of the health and environmental risks of reuse or release. This information is then used to determine the standards of quality that must be met to make the produced water fit for purpose. Finally, a user must evaluate the costs, benefits, and risks entailed in achieving those standards.

Produced water is a subject on which research is rapidly advancing, including the development of knowledge and tools for produced water characterization, treatment, risk assessment, and feasibility for reuse. Yet many knowledge gaps remain to be tackled. Strategic advancements in data and analysis will be needed to inform risk-based decisions and support the development of reuse programs that are protective of human health and the environment.

A central challenge will be researching and designing effective and economical treatment trains for specific reuse scenarios, which can entail analyzing the complex character of a specific produced water; managing variability; significantly reducing high total dissolved solid levels, organic constituents, metals, and naturally occurring radioactive material; and handling residuals. The most purposeful and actionable research and development strategy will be to identify and focus on specific reuse options where circumstances align to make reuse a potential need or opportunity in the near-future, in specific regions, taking into account the volume and quality of produced water potentially available and the needs of nearby water users.

For reuse within the oil and gas industry, research needs are more modest, addressing such areas as optimized leak detection systems, water treatment technologies to cost effectively address specific water quality challenges related to scale buildup or a specific analyte or other component, improvements in enhanced evaporation or desalination, development of automated treatment systems that can be operated remotely with little or no human intervention, and methods for separation of saleable products during treatment.

Overview of Regulatory and Legal Challenges and Opportunities

Nearly every aspect of produced water — including management practices, construction standards, and operational requirements — is regulated by federal, state, or local agencies. Disposal of produced water through surface discharges or injection in underground wells is subject to two key federal permitting programs — the National Pollutant Discharge Elimination System (NPDES) program and the Underground Injection Control (UIC) program — both of which are administered primarily at the state level.

Presently, regulatory frameworks for overseeing beneficial use of produced water, particularly reuse outside the oil and gas industry, are not well developed. As interest in beneficial reuse of produced water grows, agencies could be expected to develop new regulatory programs to authorize and manage those activities. Legal and regulatory considerations include determining state water rights as well as applicable regulations such as those relating to water quality standards and permitting. The determination of a specific beneficial use would depend on federal and state jurisdiction and the circumstances of each case.

Similarly, midstream water operations and other forms of water sharing are often outside traditional state oil and gas regulatory frameworks and require state authorization and oversight for activities that are not associated with other permitted oil and gas operations. Expanding midstream and other water-sharing opportunities may require state-level regulatory or legislative solutions to several issues, including management of risk associated with commercial management of large volumes of produced water from multiple sources at one facility, ownership of produced water, transfer of ownership, surface storage, and determination of liability if there is a spill or other environmental damage.

There are also other concerns regarding ownership and legal liability. In many cases, the lease holder, typically an oil and gas company, is the owner of the produced water and has the legal liability to properly treat, transport, and dispose of it. Reuse within the oil and gas industry is typically not subject to additional regulations other than tracking the flow and disposition of the produced water. However, if treated produced water is being reused outside the oil and gas industry, there must be a clear understanding of the current and future liability and transfer point of the liability and ownership.

Conclusions

Operators and regulators alike are rethinking the economics and long-term sustainability of traditional produced water management practices. Many operators are reusing more produced water than ever. As water becomes scarcer, the increasing benefits of reusing produced water in some regions may outweigh the costs of managing, treating, storing, and transporting it if health and environmental risks can be understood and appropriately managed. While most near-term alternatives focus on reuse of produced water to reduce fresh water consumption in unconventional oil and gas operations, interest is growing in the potential for reuse outside the oil and gas industry.

Produced water is not uniform, and neither are the circumstances of its potential treatment and reuse. Research, treatment decisions, risk management strategies, and in some cases even approval processes should be tailored to address the reuse of a particular produced water for a particular type of reuse. Identifying specific reuse options that address current or emerging needs or drivers in specific regions is an important next-step opportunity in order to prioritize investment in purposeful and actionable research and development with a defined set of facts and circumstances. Additional regulations to protect public health and the environment may apply or be developed in response to increased beneficial reuse outside the oil and gas industry.

Introduction

Produced water, a byproduct of oil and gas production, is water in underground formations that is brought to the surface during oil and gas production. It is sometimes referred to as "brine" or "saltwater" within the industry, as it is typically saline to highly saline (Figure I-1).

Water Quality	TDS (mg/L)
Fresh	<1,000
Slightly saline	1,000-3,000
Brackish	3,000-10,000
Saline	10,000-35,000
Highly saline	>35,000

Figure I-1. Produced Water Quality
Source: After USGS and Compendium of Hydrogeology
Produced water salinities range from fresh to highly saline.

While most produced water is groundwater naturally occurring deep in the reservoir, it also can include water previously injected into the formation during well treatment or secondary recovery to increase oil and gas production, as well as residuals of any chemicals added during the production processes. A third source of produced water is "flowback water" that returns to the surface after a well is hydraulically fractured.

Produced water is classified as an "exempt" oil and gas waste stream, meaning it is not subject to the Subtitle C (hazardous waste) provisions of the Resource Conservation and Recovery Act (RCRA). Its management is subject to two key federal permitting programs—the National Pollutant Discharge Elimination System (NPDES) program and the Underground Injection Control (UIC) program—both of which are administered primarily at the state level.

Produced water is either disposed of as a wastewater or beneficially reused (Figure I-2). In cases where it is determined to be fit for a beneficial reuse, produced water then becomes a resource rather than a waste product. Over the past decade, interest has grown in increasing the beneficial reuse of produced water both inside the oil and gas industry and elsewhere, an approach that holds promise for making available a substantial volume of water that could potentially offset, or supplement, fresh water demands in some areas.

The GWPC anticipates that as states and regions look to become more water resilient, the role of produced water will expand. To encourage this expansion, this report compiles information regarding produced water and identifies areas of needed legal or regulatory action and where research needs exist to potentially increase the amount of produced water utilized. It is hoped that over time this report will be used to:

- Educate the public on produced water and how the oil and gas industry uses water
- Encourage the oil and gas industry, state and federal regulatory agencies, and other parties that gather data on produced water to make the data more readily available
- Inform new research in the chemical characterization of produced water
- Inform new research to determine appropriate quality objects for reuse of produced water
- Inform new research in the development and testing of technologies for the treatment of produced water
- Expand the use of produced water in a manner that is protective of the environment and public health.

What Is Driving the Discussion of Produced Water Reuse?

Several factors are driving the discussion about the reuse of produced water, including stress on fresh water resources, limitations on underground formation storage capacities and pressures, concerns about

DIFFERING STATE DEFINITIONS OF FRESH WATER

Legal/regulatory definitions of fresh water differ by state. For example, the Pennsylvania Department of Environmental Protection defines fresh water as “Water in that portion of the generally recognized hydrologic cycle which occupies the pore spaces and fractures of saturated subsurface materials.” The Texas Water Development Board defines fresh groundwater as water with less than 1,000 mg/L of Total Dissolved Solids (TDS), while the Wyoming Oil and Gas Conservation Commission defines fresh water as “water currently being used as a drinking water source or having a total dissolved solids (TDS) concentration of less than 10,000 milligrams per liter (mg/l) and which can reasonably be expected to be used for domestic, agricultural, or livestock use; or is suitable for fish or aquatic life.”

Determining what is considered “fresh water” depends on the quality of the water, the state in which the water resides, and the use of the water. Since it is not possible to use a single definition for fresh water, the term “fresh water” in this report must be viewed within the context of the narrative in which it appears.

induced seismicity, and localized need for large volumes of water for unconventional oil and gas operations such as hydraulic fracturing.

From a technical standpoint, “fresh water” is defined by both the U.S. Geological Survey (USGS) and the Compendium of Hydrogeology[1] as water that contains less than 1,000 milligrams per liter of dissolved solids (TDS). The USGS goes on to note that “generally, more than 500 mg/L of TDS is undesirable for drinking and many industrial uses”,[2] and the EPA has established a secondary drinking water standard of 500 mg/L TDS.

Fresh water stress is driven by rising populations and regional droughts, which have created challenges to meet demands for fresh water resources in some areas across the country. According to the U.S. Census Bureau, the U.S. population is expected to increase by more than 50 million between 2000 and 2020. Where surface water is scarce, communities and industries typically turn to groundwater to meet their freshwater needs. Currently, there are concerns about the amount of groundwater being used regionally and nationally. For example, as of 2015, storage in the

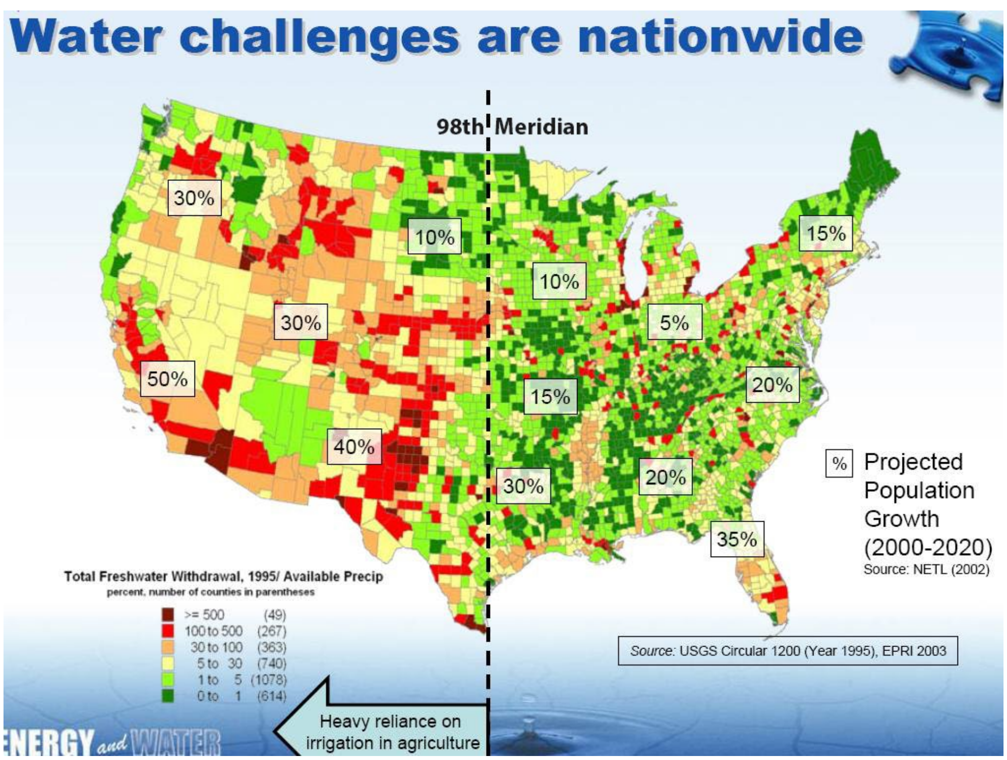

Figure I-2. Fresh Water Withdrawals and Population Growth Estimates

Source: https://myweb.rollins.edu/jsiry/Waterbasics.html

This figure shows the total freshwater withdrawal divided by the available precipitation in different parts of the country. The anticipated percentage population increases in different regions is overlain on the map. Much of this growth is projected to occur in the already water-stressed areas of the Southwest. The 98th Meridian shown on the map illustrates an important distinction for the management of produced water.

1 Robert F. Porges and Mathew J. Hammer, *The Compendium of Hydrogeology* (Westerville, Ohio: National Ground Water Association, 2001).

2 “Water Science Glossary of Terms,” The USGS Water Science School, U.S. Geological Survey, https://water.usgs.gov/edu/dictionary.html.

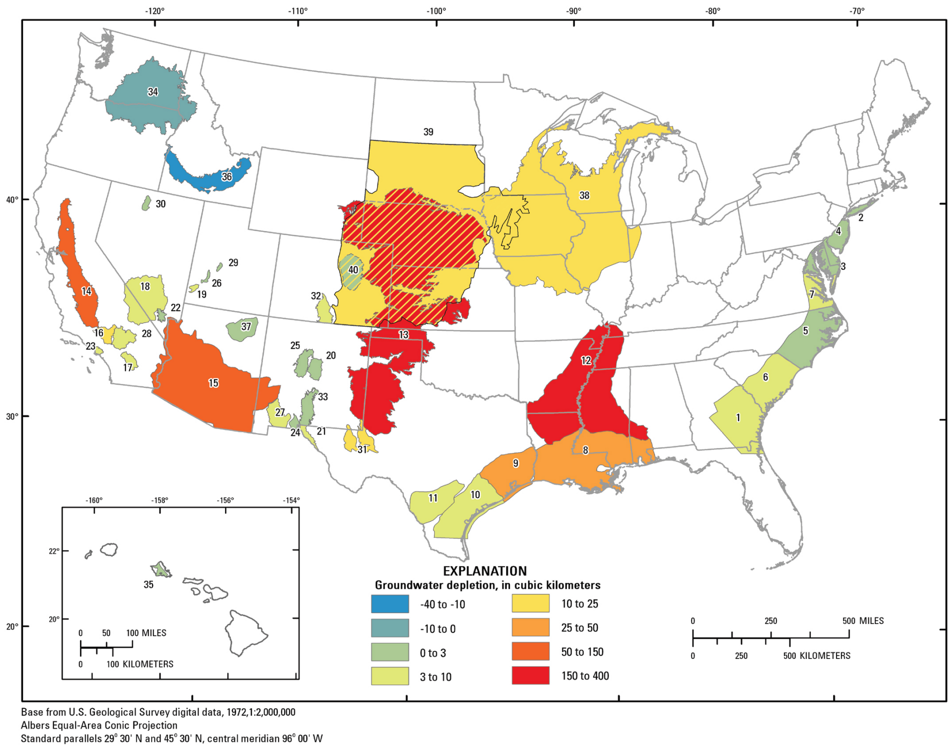

Figure I-3. Cumulative Groundwater Depletion, 1900 through 2008, in 40 Assessed Aquifer Systems or Subareas in the United States (excluding Alaska)

Source: Groundwater Depletion in the United States (1900-2008), USGS Scientific Investigations Report 2013-5079

Fresh water withdrawals coupled with population growth have resulted in an increased reliance on groundwater resources, causing depletion of aquifers to varying degrees. This depletion (often referred to as aquifer mining) is resulting in a shortage of fresh groundwater available for use. In this figure, colors are hatched in the High Plains aquifer (area 39) where the aquifer overlaps with other aquifers having different values of depletion.

High Plains aquifer was about 2.91 billion acre-feet or more. This represents a decline of about 273.2 million acre-feet, or 9 percent, since significant groundwater irrigation development began around 1950.[3] On a national scale, approximately 1,000 cubic kilometers (km^3) of groundwater, or about 811 million acre-feet, were depleted between 1900 and 2008.[4] Once depleted, this water is not easily or quickly recharged naturally.

How Much Produced Water Is Generated?

Currently, the volume of produced water is small compared to total U.S. daily water use, but these volumes can be locally significant.[5] Based on the best available data from 2012, the nearly 1 million producing oil and gas wells in the United States generate approximately 21.2 billion barrels (bbl.) of produced water each year. Expressed in other units, this volume equals 58 million bbl./day, 890 billion gallons/year, 2.4 billion gallons/day, or 2.7 million acre-feet/year.

Produced water flow rate varies throughout the lifetime of an oil or gas well. Most unconventional hydraulically fractured wells show a high produced water flow rate initially as the flowback of fracturing fluids is occurring, followed by a decline in flow rate until it levels off at a relatively steady lower level.

Based on the best available data from 2012, the nearly 1 million producing oil and gas wells in the United States generate approximately 21.2 billion barrels of produced water each year.

Conventional oil and gas wells show little or no produced water initially, with the flow rate increasing over time. Total lifetime water production is typically higher for conventional wells than for unconventional wells.

Although this report does not include water production from coalbed methane wells, it is worth noting

3 USGS, "High Plains Aquifer Groundwater Levels Continue to Decline" (News Release, June 16, 2017), https://www.usgs.gov/news/usgs-high-plains-aquifer-groundwater-levels-continue-decline.

4 Leonard Konikow, *Groundwater Depletion in the United States 1900-2008, USGS Scientific Investigations Report 2013-5079* (Reston, Virginia: U.S. Geological Survey, 2013), https://pubs.usgs.gov/sir/2013/5079/SIR2013-5079.pdf.

5 John Veil, *U.S. Produced Water Volumes and Management Practices in 2012* (Groundwater Protection Council, April 2015), (accessed June 16, 2016) http://www.gwpc.org/sites/default/files/Produced%20Water%20Report%202014-GWPC_0.pdf.

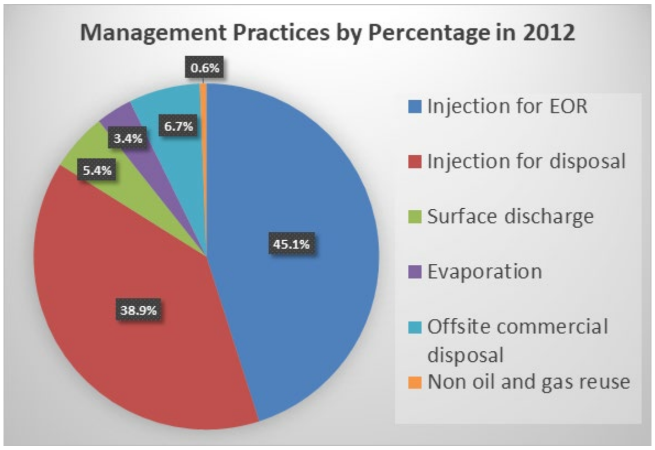

Figure I-4. Management Practices of Produced Water by Percentage in 2012

Source: GWPC 2015 Produced Water Report

In 2012, the amount of produced water generated from oil and natural gas development onshore and offshore in the United States was estimated to be 21 billion barrels. The GWPC estimates this produced water was managed as shown above.

that initial water production from these wells can be quite substantial, tapering off as gas begins to flow into the wellbore.[6]

What Does Produced Water Contain?

The physical and chemical properties of produced water vary considerably depending on the geographic location of the field, the geologic formation, and the type of hydrocarbon product being produced. Because the water has been in contact with hydrocarbon-bearing formations for millennia, it generally contains some of the chemical characteristics of the formations and the hydrocarbons in those formations.

Produced water can contain many different constituents. In collecting data for its 2016 hydraulic fracturing study, the U.S. Environmental Protection Agency (EPA) found literature reports showing the detection of about 600 different chemicals in some produced water samples.[7] Some of these chemicals are monitored routinely, while others may rarely be measured. Although hundreds of chemicals could be used as additives, only a limited number are routinely used in well treatment operations. While it is relatively easy to characterize some constituents in produced water, it is more difficult to characterize others, especially in highly saline matrices. Produced water characterization is an evolving science.

Produced water may contain:

- Mineral salts including cations and anions dissolved in water (often expressed as salinity, conductivity, or total dissolved solids [TDS])
- Organic compounds including volatile and semi-volatile organics, hydrocarbons, organic acids, waxes, and oils
- Inorganic metals and other inorganic constituents including compounds such as sulfate and ammonia
- Naturally-occurring radioactive material (NORM) that leached into the produced water from some formations or precipitated due to water mixing
- Chemical additives to improve drilling and production operations
- Transformational byproducts that can form from the interaction between added chemicals and formation water.

Another concern are constituents resulting from chemical reactions that can occur when produced water from one formation is introduced into a different formation. Additionally, naturally occurring elements, including metals, can leach out of the geologic formation into the produced water because of this change in the formation waters.

In collecting data for its 2016 hydraulic fracturing study, the U.S. Environmental Protection Agency found literature reports of about 600 different chemicals in some produced water samples.

Although some produced waters have a low salt content, most is highly saline. TDS in different produced waters ranges from less than 3,000 mg/L to over 300,000 mg/L. Waters with very high salinity are difficult to treat, and treatment results in a large quantity of very concentrated waste products that require appropriate disposal. High salinity also can

6 Cynthia Rice and Vito Nuccio, "Water Produced with Coalbed Methane," USGS Fact Sheet FS-156-00 (November 2000), https://pubs.usgs.gov/fs/fs-0156-00/fs-0156-00.pdf.

7 USEPA, *Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States, Main Report* (EPA/600/R-16/236fa), https://cfpub.epa.gov/ncea/hfstudy/recordisplay.cfm?deid=332990.

be troublesome when analyzing many constituents in produced water, since some traditional analytical methods do not work accurately in saline water. Further, adequate analytical methods may not exist for other chemicals that are not monitored frequently or are unknown at this time.

Produced water, especially from unconventional wells, will show varying concentrations of constituents over time. This consideration is important when designing treatment processes and in assessing the suitability of the produced water to be used or reused for a beneficial purpose.

What Opportunities Exist for Beneficial Reuse?

Currently, about 45 percent of produced water generated from onshore activities in the United States is reused within conventional oil and gas operations, where it is injected into formations to enhance recovery. Enhanced recovery techniques include injecting water or steam into the formation to maintain pressure and help sweep more oil to the production well ("water flooding" or "steam flooding"). Produced water is typically used for these operations, along with additional water.

Most of the remaining produced water, approximately 55 percent (488 billion gallons per year), is handled as a wastewater. Additional potential opportunities exist both within and outside of the oil and gas industry to make beneficial reuse of some of this water.

Within the oil and gas industry, operators and regulators are seeking ways to increase the beneficial reuse of produced water not only in enhanced recovery in conventional oil and gas operations, but also in well drilling and hydraulic fracturing operations in unconventional oil and gas production.

Several factors make beneficial reuse within the industry appealing in many cases. One major driver is a desire to minimize disposal of produced water. Disposal through underground injection is a costly operation that can be subject to capacity limitations. Underground injection may also create the potential for induced seismicity, which has resulted in further limitations on injection volumes and rates in some states. Disposal through discharge to surface water may be subject to volume limitations and entail costly treatment in a wastewater treatment facility or a centralized industrial wastewater treatment plant. There are also costs and risks associated with transportation of produced water. In contrast, beneficial reuse within the oil and gas operations eliminates or reduces treatment and some transportation of the produced water.

Another driver to consider is local water needs. Drought conditions in recent years have created serious water availability problems for some communities. For example, parts of the southeastern United States faced summer brown-outs due to inadequate cooling water for electrical generation, and numerous cities and towns, especially in California, Oklahoma, and Texas, have been forced to ration water. One possibility for dealing with fresh water shortages may be to supplement or replace fresh water use in unconventional oil and gas operations with produced water. (In contrast, disposal of produced water through deep injection can exacerbate water shortages since water is effectively removed from the ecosystem.)

CONVENTIONAL VS. UNCONVENTIONAL OIL AND GAS OPERATIONS

Historically, most oil and gas wells were drilled to intercept pools of oil and gas trapped in underground geologic structures. Typically, the oil and gas had migrated from their original source rock formations to other formations that had enough pore space to hold economic quantities of the hydrocarbons. These are known as "conventional" plays and the wells drilled in such areas are called conventional wells, representing historic oil field activities.

Geologists knew for decades that source rock formations, like shale, held extensive quantities of oil and gas. Because of the low permeability in the shale source rock, the historic technology for drilling wells and producing the oil and gas did not generate enough quantities to justify the cost of the wells. A few decades ago, the technologies of horizontal drilling (drilling a vertical well until just above a target formation, then turning the well so it runs horizontally or laterally within the target formation) and hydraulic fracturing (using pressure to create new cracks in a formation to allow the oil and gas to move to a well) were combined. This approach allowed wells to produce enough oil and gas from the shale formations to justify the cost of drilling and completing the wells. This type of geologic formation play is known as an "unconventional" or "tight" formation, and the wells drilled in these formations are called unconventional wells.

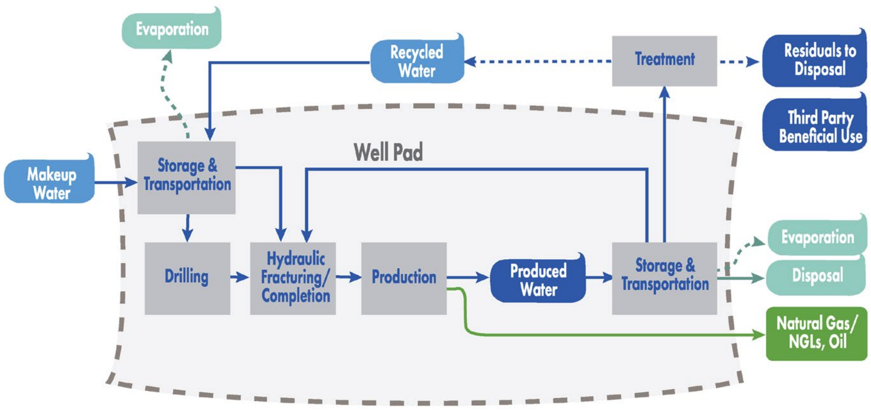

Figure I-5. Water Lifecycle for Unconventional Oil and Gas Production

Source: Energy Water Initiative (an effort by members of the U.S. oil and gas Industry to study and Improve lifecycle water use and management in upstream unconventional exploration and production)

Water is required to conduct various steps in the production of unconventional oil and gas resources. Water is needed to make up drilling and completion fluids and to assist in site washing and dust control activities. After wells are drilled, they may undergo hydraulic fracturing as part of completing the well, which requires additional water to make up the fluids used for fracturing (frac fluids).

Outside the oil and gas industry, produced water is used in a few limited applications such as livestock watering, stream augmentation, and irrigation of selected crops. Less than one percent of produced water is currently reused in such ways. Wider uses may also become practical and cost-effective with further research. As the volume of available fresh water continues to diminish, there is a growing need to reduce the use of freshwater for industrial, municipal, and agricultural activities, especially for consumptive uses that do not return water to usable water sources. Possibilities include applications in drought relief, fire protection, dust suppression, irrigation of additional crops, irrigation of public access areas such as golf courses and parks, industrial cooling or process water, mining, municipal water needs, and recreational uses.

Generally, beneficial reuse outside the oil and gas industry will be less economically attractive than reuse within the industry, since the produced water usually must be transported greater distances and treated more extensively. (See Module 3 for more information about reuse outside of oil and gas operations.)

What Factors Determine the Feasibility of Beneficial Reuse?

Because produced water resides at the surface, it makes sense to determine whether there is a cost-effective and environmentally friendly way to treat and reuse it instead of disposing of it by underground injection. Several factors determine whether and where beneficial reuse is feasible.

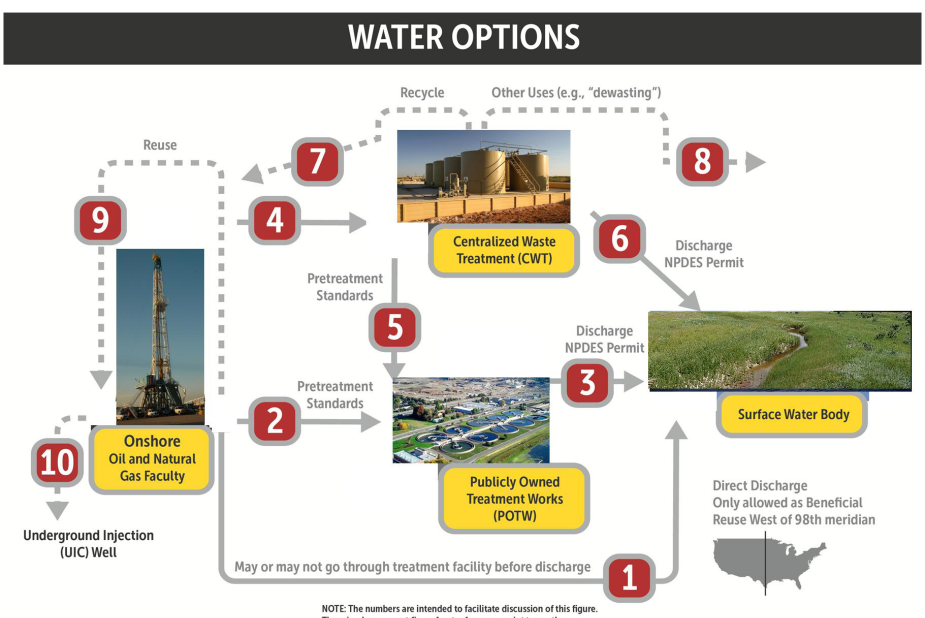

Figure I-6. Options for Produced Water Management

Source: After American Petroleum Institute (Modified)

This figure illustrates the range of alternate options for managing produced water. Options 1 through 6 show some form of discharge to surface waters, either directly or after treatment in a wastewater treatment facility or a centralized industrial wastewater treatment plant. Produced water can be used again in the oil and gas process without treatment (option 9) or after treatment (option 7). Produced water can also be put to some other use (option 8) after treatment. Option 10 shows produced water directed to injection wells. A more substantive discussion of these practices is included in Modules 1 and 2.

Currently, more than 90 percent of the produced water brought to the surface from the production of oil and gas is injected underground through Class II injection wells such as the one shown here to aid in future oil and gas production or for disposal.

Water quality. The quality of produced water will determine its potential suitability for specific uses. A major water quality consideration is the feasibility and cost of treating the produced water to be fit for the intended purpose. In some cases, research may be necessary to define quality goals. Produced water from different sources varies greatly in quality and its reuse requires accurately characterizing the constituents and their concentrations in a specific produced water supply, identifying the health and environmental risks of their release, determining the standards of quality that must be met to make the produced water fit for purpose, and evaluating the costs, benefits, and risks entailed in achieving those standards. Management of treatment residuals is a major cost factor and can present a substantial barrier to water treatment based on its characteristics, volumes, and disposal options.

Water quality presents a lesser challenge for reuse within oil and gas operations, because this option presents limited exposure pathways, operators have a good understanding of quality needs or objectives, and there are reduced treatment requirements.

Water volumes and longevity. The amount of produced water and its long-term availability can affect the desirability of its reuse. While desirability may be high in an area with large amounts of produced water and limited alternate water supplies, that is not likely to be the case where produced water volumes are low, and supplies are unpredictable. Longevity of supply is especially important in making the case for beneficial reuse outside the oil and gas industry. For example, a typical production well may last from 20 to 30 years, while a typical coal fired power plant has a lifespan of 50 years or more. Unless the operator(s) can guarantee a quantity of deliverable water of a specific quality over the life of the power plant, it may not be advantageous for the power plant to use produced water as a source of supply unless a separate guaranteed backup source of supply can be arranged.

Logistics and infrastructure. Logistical and transportation costs may limit the potential reuse of produced water. Considerations include the availability of treatment facilities and the costs of transporting the produced water to the facilities as well as to the point of end use. Moving water can be expensive. Trucking costs for a typical trip from a tank battery to a salt water disposal (SWD) well can range from $1 to $3 per barrel.[8] The cost of constructing permanent pipelines currently averages about $1.45 million per mile depending on pipe size, terrain, right of way costs, and other factors.[9] The use of temporary pipe, sometimes

FIT FOR PURPOSE

The level of treatment necessary when considering reuse of produced water depends on the quality needs for the intended use. Treatment is typically designed to be "fit for purpose."

If salinity reduction or removal of other constituents of concern is needed to meet a regulatory standard (e.g., discharge to a river) or if the end use requires water with a specific set of parameters, advanced treatment may be necessary to meet those end goals.

If the produced water will be injected into a disposal well or back into a formation to produce more oil, less or possibly no treatment is needed. The main treatment goals are to remove any free oil or large solids to keep the injected water from blocking the pores in the formation or damaging the injection equipment and to remove any other constituents that may interfere with drilling or completion.

8 One barrel (bbl.) equals 42 gallons.

9 State of Oklahoma Water Research Board (OWRB), *Oklahoma Water for 2060 Produced Water Reuse and Recycling* (Tulsa, Oklahoma: April 2017), https://www.owrb.ok.gov/2060/PWWG/pwwgfinalreport.pdf.

referred to as "lay flat pipe", is less expensive than permanent pipe but comes with its own set of problems, including increased maintenance needs and higher leakage rates. Remote locations may require the use of modular treatment facilities where the logistics of transporting water to a centralized facility may be both difficult and cost prohibitive. The extent to which this affects beneficial use depends on the availability and cost of modular treatment, accessibility to the site, number of treatment units needed, maintenance needs of the treatment equipment, and other factors.

Market considerations. The economic attractiveness of beneficial reuse depends on whether the supply of produced water is predictable, if it can be delivered reliably to the point of use, and how the cost compares to other available sources of water after factoring in the costs of its treatment and transportation as well as the disposal of treatment residuals. If local water supplies of freshwater are adequate or abundant, there is less incentive to consider beneficial reuse of treated produced water, especially given its associated risks. Also, when other water sources, such as locally available brackish groundwater, can be delivered cost effectively, that may also depress reuse of produced water.

Legal and regulatory. These considerations include determining state water rights as well as applicable regulations. The determination of a specific beneficial use depends on federal and state jurisdiction, and the circumstances of each case.[10] Another concern is the legal liability. In many cases, the lease holder, typically an oil and gas company, has the legal liability to properly treat, transport, and dispose of the produced water. However, if treated produced water is being used or reused outside of the oil and gas processing areas, there must be a clear understanding of the current and future liability and transfer point of liability.

What Are Future Implications for Water Planning?

Realizing the promise of increased beneficial reuse of produced water will not be a simple matter. It will require addressing substantial economic, technical, regulatory, and environmental challenges.

Given these complex factors, it would be unrealistic to suggest that all produced water can be put to beneficial reuse. Yet it is important for policymakers to recognize all the potential sources of water in an area to meet user needs. When considered as an integral part of water planning, treated produced water can be utilized to help relieve reliance on fresh water.

Based on the location, volume, and availability of fresh water, treated wastewater and produced water can, and likely will, play a larger role in future water supplies. However, until further research is completed, opportunities to reuse produced water more widely may be limited. Additional research on the characteristics of produced water in specific locations and evaluation of the environmental and health risks that could be associated with produced water use will be necessary to help inform both producers and potential end users of the possibilities for expanded produced water reuse.

In addition to research, challenges to be addressed range from defining regulatory frameworks to gaining public acceptance of produced water use in new applications. Presently, regulatory frameworks for overseeing beneficial use of produced water are not well developed. GWPC anticipates that as interest in beneficial use of produced water grows, agencies will develop new regulatory programs to authorize and manage those activities.

10 Modified from "Produced Water Treatment and Beneficial Use Information Center" website, Colorado School of Mines / Advanced Water Technology Center, http://aqwatec.mines.edu/produced_water/intro/what/index.htm.

Why Isn't Coalbed Methane Produced Water Included in this Report? Water from coalbed methane production is not included in the report for several reasons:

- Because the volume of coalbed methane produced water falls off rapidly after initial production, it is not a reliable potential long-term source of water for reuse, except for hydraulic fracturing of other coalbed methane wells.
- Coalbed methane production operations are generally distant from major oil and gas producing basins, making its use in exploration and production activities impractical except for fracturing of other coalbed methane wells.
- Coalbed methane produced water is not covered by the oil and gas Effluent Limitation Guidelines (ELGs) promulgated at 40 CFR Part 435 and is frequently fresh enough to be considered for surface discharge with minimal treatment. Reuse can be logistically more difficult and costlier than such discharge.
- Contributions of produced water from coalbed methane would likely be statistically insignificant. Volumes of coalbed methane production continue to decline nationally and are small (< 3% annually) compared to natural gas production.

Studies on coalbed methane produced water are acknowledged in this report where relevant but are not extensively analyzed.

MODULE 1

Current Legal, Regulatory, and Operational Frameworks of Produced Water Management

MODULE SUMMARY

This module explores the use of water in the oil and gas industry from a national overview perspective and describes the regulatory frameworks surrounding management of produced water. Essential points about regulatory management of produced water include the following:

Water is critical to oil and gas production.
Water plays an integral role in oil and gas production, including use for drilling fluids, fracturing fluids, and water flooding. Produced water is generated from producing wells and must be managed. Historically, more than 90 percent of produced water is injected underground for disposal or to help produce more oil.

States regulate oil and gas activity.
The entire oil and gas exploration and production process is regulated in many ways by different agencies, with most oil and gas regulation occurring at the state level. The principal purpose of these regulations is to protect the environment. While some produced water management activities are subject to regulatory standards, others are subject to operational standards set by operators or end users. There are more than 30 states with oil and gas production, and each state has its own regulations. Even within individual states, more than one agency may regulate the management of produced water, as shown in Table 1-3.

Water rights and responsibilities vary from state to state.
Produced water is groundwater and is subject to individual state water rights laws. Each state has a different set of laws governing the management and allocation of surface and groundwater. Views on reuse of produced water vary depending on which state is involved, as shown in Table 1-4.

It is important to identify how and when ownership changes occur and to understand that these changes in ownership may differ based on local or state regulations or laws. Understanding the role of water rights, mineral rights, and surface ownership in the exploration and production of oil and gas is critical in addressing how and when there is compensation for or liability related to the beneficial use of produced water.

Produced water reuse requires careful thought.
Reuse of produced water is possible and may be cost effective in the right situations. When specific reuse projects are being considered, oil and gas companies and end users must work together. Regulators can look for ways to allow reuse projects to move forward but should ensure that these practices can be done with proper environmental and public health protection.

Expanding reuse opportunities may require regulatory or legislative solutions to several issues, including ownership of produced water, transfer of ownership, and determination of liability if there is a spill or other environmental damage.

Background

Water is closely intertwined with oil and gas production, including water supplied to support operations and byproducts (produced water) from the production process. Determining how to find source water and manage produced water efficiently and cost effectively is an important component of producing oil and gas.

Nearly every aspect of produced water—including management practices, construction standards, and operational requirements—is regulated by federal, state, or local agencies. Federal laws and regulations govern the disposal of produced water through surface discharges or injection in underground wells.

Oil and gas companies are required to obtain numerous permits, licenses, and certificates, conduct monitoring and reporting to the agencies, and operate in compliance with the regulations. Produced water can be managed within an individual lease area or over a larger field that incorporates many wells and leases. Depending on the size of fields or plays, more than one oil and gas company may be involved, and geographic boundaries can include more than one county, river basin, or state.

Following are examples of regulatory involvement throughout the oil and gas water cycle.

- **Sourcing, including ownership of water.** State water rights laws or regulations determine who has legal rights to water sources. Many states require permits to withdraw water from surface or groundwater sources. Under drought conditions, permits may be delayed or denied temporarily, or allocations may be reduced. If water is obtained from a municipal drinking water supplier, municipal wastewater treatment facility, or other alternate source, contracts or some other legal mechanisms are utilized.
- **Transportation of water.** Trucks used to haul water must obtain permits and licenses. When pipelines are used, they typically are long, linear structures that may cross over areas owned by multiple landowners, requiring multiple easements to be purchased or leased. Where pipelines intersect roadways, streams, railways, or other existing structures, additional permits and approvals are typically needed.
- **Storage of water.** In some states, permits are required to build and operate storage pits which are subject to construction criteria, including surface water and groundwater contamination prevention. When tanks are used, they typically are authorized as part of the Application for Permit to Drill or by rule. Although most states do not have specific design and construction requirements for tanks, secondary containment requirements are required in almost all cases. Spill prevention, control, and countermeasure (SPCC) plans may be required. Additionally, stormwater management permits may be required for the storage at the well site.
- **Hydraulic fracturing**. Hydraulic fracturing is typically regulated under state oil and gas programs. Reporting of information relating to pressures, volumes, depths, duration, materials, etc., must be made for each hydraulic fracturing job. In many states, companies conducting fracturing jobs must keep information available, submit information to the state regulatory agency, or enter data on water and chemical usage into the National Hydraulic Fracturing Chemical Registry (FracFocus). Transportation and storage of chemicals used in fracturing fluids may be regulated by federal, state, and local agencies.
- **Disposition of produced water**. Produced water disposed by discharge directly to surface water must be authorized by a National Pollutant Discharge Elimination System (NPDES) permit and/or a state discharge permit. Produced water sent to a municipal wastewater treatment facility must follow NPDES regulations for pretreatment and meet any additional standards imposed by the wastewater treatment facility. Currently, this is only allowed when produced water is pretreated at a centralized treatment facility or is generated through conventional oil and gas activities. Produced water sent to a centralized treatment facility must meet any standards established by the treatment

facility, and the centralized treatment facility must meet standards established in its NPDES or state discharge permit. Wells used to inject produced water for enhanced recovery must be permitted under the Underground Injection Control (UIC) program as Class II-R UIC wells. Produced water sent to Class II disposal wells may be subject to state tracking regulations. The disposal wells themselves must be permitted as Class II-D UIC wells. If water is placed in pits and disposed of by evaporation, there may be construction, operational, and air quality permits required.

- **Beneficial use of produced water.** Beneficial use within the oil and gas industry is typically not subjected to additional regulations other than tracking the flow and disposition of the produced water. Existing beneficial uses of water in applications outside of the oil and gas industry may be subject to permits. For example, several states allow for and regulate the spreading of produced water on roads during winter months for snow and ice control. In Ohio, for example, minimum state standards for produced water spreading are established, but spreading must be authorized by resolution of the local authority that has jurisdiction over road maintenance. Local authorities can adopt standards that are more stringent than the state standards and may rescind authorization. Use of produced water for irrigation or industrial use may be subject to state regulations. As beneficial use of produced water is considered for more applications such as crop irrigation, stream augmentation, industrial cooling towers, etc., it is likely that additional regulations will be adopted.

This module describes the major federal laws and regulations affecting produced water, specifically the NDPES and UIC programs, as well as the cooperative relationship between federal and state governments to administer these laws and regulations. In addition, it discusses regulations at the state level that cover produced water reuse practices. Some states have such regulations, but most do not. States often differ in their regulatory approaches, reflecting geologic or other physical differences among states. This module is not intended to be a comprehensive compilation of state produced water management regulations. Rather, it is designed to provide the reader a sense of the scope of regulatory, operational, and legal standards that apply to produced water in regions of the United States.

WASTEWATER TREATMENT FACILITIES

Most communities operate facilities to treat sewage, with such names as municipal sewage plant, wastewater treatment plant, publicly owned treatment works (POTWs), water resource recovery plant, and water reclamation facility. In this report, the term "wastewater treatment plant" is used in most instances. In a few situations, the term POTW is used because it is noted as such in related documents. Readers should understand that these are the same type of facility.

There are also industrial wastewater treatment facilities and centralized treatment facilities that treat produced water prior to disposal, discharge, or reuse. These often employ different types of treatment equipment than traditional municipal wastewater facilities because they are designed to treat industrial wastewater.

The U.S. Legal/Regulatory System

The federal legal/regulatory system in the United States consists of three tiers. The interrelationships of these tiers can be seen in the example of regulation governing the discharge of produced water to rivers, lakes, and streams. At **Tier 1**, Congress passed the Federal Water Pollution Control Act, later known as the Clean Water Act (CWA), which created the National Pollutant Discharge Elimination System (NPDES) program to regulate any discharge of wastewater to water bodies that are waters of the United States. As the designated federal agency, the EPA established comprehensive regulations (**Tier 2**) for implementing the NPDES program. NPDES water quality permits (**Tier 3**) are either issued by the EPA itself (in Massachusetts, New Hampshire, New Mexico, the District of Columbia, and U.S. territories, as well as on federal and tribal trust lands) or by states that have been delegated by EPA to issue their own permits, including for produced water discharges.[11]

11 USEPA, Map of NPDES Program Authorizations (July 2015), https://www.epa.gov/sites/production/files/2015-10/documents/state_npdes_program_status.pdf.

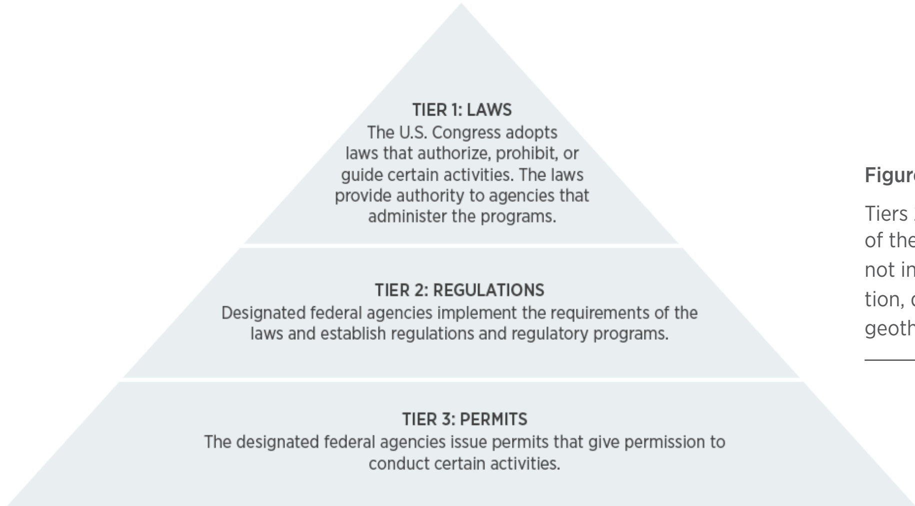

Figure 1-1. U.S. Federal Legal/Regulatory System

Tiers 2 and 3 are dependent on the basic authority of the CWA. NPDES delegation in some states does not include activities associated with the exploration, development, or production of oil or gas or geothermal resources.

Federal Laws and Regulatory Programs

Two federal regulatory programs are historically associated with management of produced water:

- **The National Pollutant Discharge Elimination System (NPDES) program.** Through the Clean Water Act (CWA), the U.S. Congress directs the EPA to create an NPDES permitting, compliance, and enforcement program that regulates discharges of produced water to rivers, lakes, and streams. The CWA also allows the EPA to delegate authority to states and tribes that demonstrate financial, managerial, and technical competency. States customize the NPDES program based on state specific laws, hydrology, weather conditions, and other factors. When states are authorized to operate the program, typically it is renamed to identify the state and include any state specific requirements. For example, the NPDES program in Oklahoma is the Oklahoma Pollutant Discharge Elimination System program (OPDES). In this report, "NPDES permits" includes those permits issued by a state under the delegated authority.
- **The Underground Injection Control (UIC) program**. Through the Safe Drinking Water Act (SDWA), Congress directs the EPA to develop the UIC program to regulate disposal in injection wells and provides for its delegation to states under agreements with the EPA. Most oil and gas producing states have received the authority to implement UIC

Table 1-1. Comparison of ELGs for the Oil and Gas Extraction Industry

Subcategory	Parameter	Limits on Produced Water Discharges
Onshore	n/a	Zero discharge
Stripper Wells[a]	n/a	No nationwide federal discharge standards
Agricultural and Wildlife Water Use[b]	oil and grease	35 mg/L
Coastal	oil and grease	Zero discharge except for Cook Inlet, AK, which has the same limits as offshore wells
Offshore	oil and grease	29 mg/L monthly or 30-day average 42 mg/L daily maximum

a Applies to wells producing less than 10 bbl./day of crude oil. There is no comparable subcategory for small gas wells.

b Applies to onshore facilities located in the continental United States and west of the 98th meridian for which the produced water has a use in agriculture or wildlife propagation when discharged into waters of the United States. The term "use in agricultural or wildlife propagation" means the produced water is of good enough quality to be used for wildlife or livestock watering or other agricultural uses and is actually put to such use during periods of discharge.

Class II programs. In the few states where the agencies have not received authority to administer those programs, the programs are administered by the regional office of the EPA.

Delegated NPDES and UIC programs operate independently but are subject to federal oversight.

Overview of the NPDES Program

The NPDES program requires that any discharge of wastewater to waters of the United States be authorized by a permit. Permits can either be individual permits to authorize and establish regulatory controls from a single facility or general permits for multiple facilities with similar operations and discharges.

The permit specifies both narrative and numerical limits on one or more constituents in the discharged wastewater to protect the designated beneficial uses of the receiving water body. Permit limits are determined using technology-based standards and water-quality-based standards. The most protective value becomes the permit limit. In the case of permit renewals, the anti-degradation provision of Water Quality Standards may apply.

The permit writer first calculates technology-based limits, considering such factors as the constituents in the discharge, the types of treatment commonly used for the type of wastewater, and the cost of treatment. For many major industrial categories, the EPA has already done much of this work and has published national minimum discharge standards that must be met unless more restrictive state standards or water quality standards exist. These national discharge standards are known as effluent limitations guidelines (ELGs). The ELGs for the oil and gas extraction industry are published in the Code of Federal Regulations (CFR) at 40 CFR Part 435 and are shown in Table 1-1.

Further definition of the limits shown in Table 1-1 are as follows:

- Although onshore wells are subject to a national zero discharge requirement for produced water, there are several exceptions to this regulation. For example, EPA declined to establish a national discharge standard for stripper wells. Permit writers in states or EPA regional offices have discretion to allow these discharges.
- Particular limits apply to wells located west of the 98th meridian (Figure 1-2) with produced water that "is of good enough quality to be used for wildlife or livestock watering or other agricultural uses and that the produced water

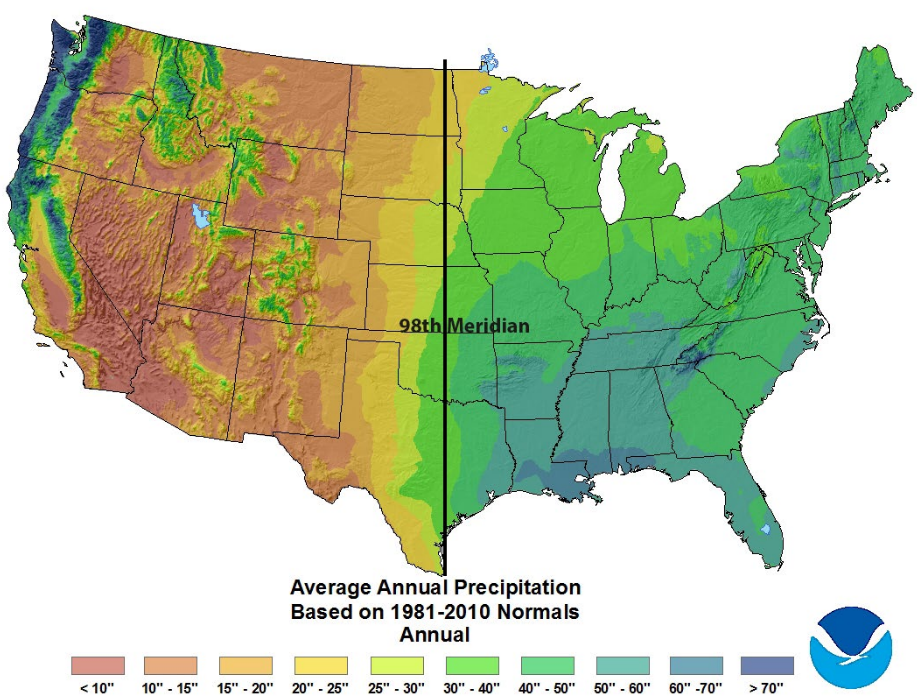

Figure 1-2. Map Showing 98th Meridian Overlain on Annual Precipitation Map
Source: Modified from National Oceanographic and Atmospheric Administration https://www.ncdc.noaa.gov/climateatlas/

The 98th meridian extends from near the eastern edge of the Dakotas through central Nebraska, Kansas, Oklahoma, and Texas.

is actually put to such use during periods of discharge."[12] Permit writers must follow the minimum oil and grease limit of 35 mg/L but can also place limits on other parameters.

- Coalbed methane (CBM) generates a lot of produced water. In many CBM fields, the water is too salty to discharge. In other places, the salinity is lower (e.g., Powder River Basin in Wyoming) or the available dilution in the local rivers is very high (e.g., Black Warrior Basin in Alabama). CBM produced waters are not subject to the oil and gas ELG.
- Most produced water east of the 98th meridian cannot be discharged directly from an oil and gas well site. It can be treated offsite in a centralized wastewater treatment facility and then discharged if the facility has been issued an NPDES (or state equivalent) permit. In a few instances, centralized facilities in cities have obtained permission to discharge treated water to the municipal sanitary sewer where it will receive additional treatment at the city's wastewater treatment facility.

Although technology-based limits and ELGs serve as a baseline for the effluent limits included in a permit, the technology-based controls may not ensure that all designated beneficial uses of the surface water will be protected. In these cases, the permit writer must include additional, more stringent water-quality-based effluent limits in NPDES permits. These limits may be numeric[13] or narrative (e.g., "no toxic substances in toxic quantities"). The process for establishing the limits considers the designated beneficial use of the water body; the amount of the pollutant in the effluent, toxicity, and assimilative capacity; and, where appropriate, dilution in the receiving water (including discharge conditions and water column properties).

Appendix 1-A describes the NPDES permitting process undertaken by an oil and gas company in Arkansas for a centralized produced water treatment facility.

UNDERGROUND SOURCES OF DRINKING WATER (USDW)

The code of Federal Regulations at 40 CFR 144.3 defines a USDW as an aquifer or part of an aquifer which:

- Supplies any public water system, or contains a sufficient quantity of groundwater to supply a public water system and currently supplies drinking water for human consumption or contains fewer than 10,000 milligrams/liter of Total Dissolved Solids (TDS); and
- Is not an exempted aquifer as defined in 40 CFR Section 146.4 as part or all of an aquifer which meets the definition of a USDW, but which has been exempted according to the criteria in 40 CFR Section 146.4.

Overview of the UIC Program

The UIC program is designed to protect underground sources of drinking water (USDWs). This protection is provided through the regulation of injection wells. An injection well is defined as any bored, drilled, or driven shaft or a dug hole, where the depth is greater than the largest surface dimension that is used to inject fluids underground. Underground injection is grouped into six classes of injection wells (Table 1-2).

Wells used for injecting produced water are Class II wells. When fluids are injected into a hydrocarbon-bearing formation to help produce additional oil (water flood, steam flood) the injection wells are Class II-R, enhanced recovery wells. Produced water can also be injected solely for disposal. In this case, the water is typically injected into a formation below the USDW other than the producing formation. These wells are known as Class II-D disposal wells. A third group of Class II wells are used to inject fluids associated with hydrocarbon storage wells (Class II-S). These are not directly related to produced water and are not discussed further here.

12 Specialized Definitions 40 CFR 435.51, *Code of Federal Regulations*, Title 40 (2003), https://www.govinfo.gov/content/pkg/CFR-2003-title40-vol27/pdf/CFR-2003-title40-vol27-sec435-51.pdf.

13 Most states have published water quality standards for many pollutants that can be used to calculate water quality-based limits. These are enforceable regulations. Where state standards are not available, permit writers can look at EPA's published numeric water quality criteria for more than 100 pollutants. These criteria are technical recommendations but are not enforceable unless they are specified in a permit.

Table 1-2. Classification of UIC Wells
Sources: USEPA and State Primacy Agencies

Underground Injection Control Well Classification Chart

Well Class	Purpose	Active Wells*
I	Injection of hazardous, non-hazardous, and municipal wastes below the lowermost USDW	817
II	Injection of fluids associated with the production of oil and natural gas resources for disposal or enhanced oil and gas recovery	180,344
III	Injection of fluids for the extraction of minerals	29,617
IV	Injection of hazardous or radioactive wastes into or above a USDW**	127
V	Injection into wells not included in the other well classes but generally used to inject non-hazardous waste	650,000 to 1.5 Mil.
VI	Injection of supercritical carbon dioxide for storage	2***
* All numbers estimated from state agency surveys and a USEPA inventory published for Federal Fiscal Year 2017. ** Class IV wells are banned except where used for remediation of USDWs *** Existing commercial wells with permits issued under the Class VI program		

Following are key elements of Class II UIC permits.

- **Well location**. This can include conditions such as depth, wellhead location, and setback distances.
- **Construction requirements.** This can include details like the size and setting depths for different layers of casing, cementing requirements, and other well hardware.
- **Area of Review evaluation.** This element includes an evaluation of the area surrounding the proposed injection well to identify any pathways for the injected fluids to migrate from the targeted injection zone.
- **Operations.** This typically includes restrictions on parameters like pressure, flow rate, and daily injected volume.
- **Monitoring and reporting to the permitting agency.** This element includes routine and periodic logging and mechanical integrity testing to ensure that wells are not leaking. Other types of monitoring and reporting may be required, including operating restrictions.
- **Closure requirements.** This element includes requirements for plugging and abandonment.

Over 90 percent of produced water generated in the United States is injected into underground geologic formations through injection wells permitted under the UIC Class II program. Under sections 1422 and 1425 of the Safe Drinking Water Act (SDWA), the EPA may delegate primary enforcement authority (primacy) to states, territories, and tribes for the UIC program. To date 43 states, territories, and tribes have obtained primacy for portions of the UIC program. Of these, 25 states and 2 tribes have obtained primacy over the Class II UIC program in areas where oil and gas exploration and production occur.

Over 90 percent of produced water generated in the United States is injected into underground geologic formations through injection wells permitted under the UIC Class II program.

The E&P Waste Exemption

EPA made an important regulatory determination in 1988 that clarified that oil and gas exploration and production (E&P) wastes, including produced water, would not be subject to Subtitle C (the hazardous waste section) of the Resource Conservation and Recovery Act (RCRA).[14] This determination was important in allowing the oil and gas industry to manage produced water in ways that made sense and were cost-effective. The determination stated in part, "USEPA's review… found that imposition of Subtitle C regulations for all oil and gas wastes could subject billions of barrels of waste to regulation under Subtitle C as hazardous wastes and would cause a severe economic impact on the industry and on oil

14 USEPA, "Regulatory Determination for Oil and Gas and Geothermal Exploration, Development and Production Wastes," Federal Register 53, no. 129 (July 6, 1988): 25447, https://archive.epa.gov/epawaste/nonhaz/industrial/special/web/pdf/og88wp.pdf.

and gas production in the U.S." The determination also stated that "EPA found most existing State regulations are generally adequate for protecting human health and the environment." Each state can set up its own regulatory programs for this waste if they do not interfere with existing authorities such as the NPDES and UIC programs.

Additionally, states routinely evaluate their existing regulatory programs through such efforts as the State Oil and Gas Regulatory Exchange (the Exchange) and the State Review of Oil and Natural Gas Environment Regulations (STRONGER) processes. These reviews help states update their programs to remain current with technological, legal, and other changes.

The extent to which the RCRA exemption expands to include produced water, its treatment, and treatment residuals in the context of new reuse scenarios outside of oil and gas operations presents a question worth considering.

The RCRA exemption applies to wastes, including produced water, that are "intrinsically derived from the primary field operations." The extent to which the exemption expands to include produced water, its treatment, and treatment residuals in the context of new reuse scenarios outside of oil and gas operations presents a question worth considering. This is an area of evolving understanding and there are currently no clear answers, primarily because the exemption has not been tested in practice and questions, to date, remain theoretical. As options to treat and reuse produced water expand, it is likely that more attention may be paid to this subject to bring further clarity.

Regulatory Roles of State Governments

With a few exceptions, oil and gas activities relating to management of oil field wastes, including produced water, are regulated at the state level rather than directly by federal agencies or regulations. When states receive primacy to administer the NPDES or UIC programs, the state regulations do not need to be identical to the federal regulations but must include conditions that offer at least the same level of protection. States can customize regulatory programs to reflect state-specific practices and laws. They can be more restrictive than federal regulations and can include regulations for activities not covered by federal regulations. This creates a scenario in which each of the approximately 31 oil and gas producing states has flexibility to regulate oil and gas operations and management of E&P wastes, including produced water, in similar but slightly different ways. For example, as of January 2018, the Texas Commission on Environmental Quality (TCEQ) had NPDES authority for most types of discharges, but not for oil and gas industry produced water. That authority remains with EPA Region 6. The Texas Railroad Commission (RRC) manages oil and gas produced water through delegated UIC Primacy for Class II wells.

Most produced water regulatory programs are assigned to oil and gas agencies or state environmental protection agencies. However, in some cases, public health agencies, state engineers, or regional water planning commissions such as the Susquehanna River Basin Commission and the Delaware River Basin Commission may play some role in regulating produced water. State wastewater programs may also cover discharges to state waters, including non-federal surface waters, groundwater, and land application. Some states have prohibitions on moving water from one river basin to another. As new produced water reuse projects are considered, the topic of inter-basin transfer of water may become important. Additionally, some states have developed wellhead or source water protection programs that apply to all potential sources of pollution. These states may have requirements for setbacks or other requirements on a case-by-case basis.

Evolution of State Regulatory Programs

After regulating produced water for many decades, states have developed similar, but somewhat different, regulations and requirements. Differences in regulations between states reflect factors such as geography, geology, and hydrology; climate; state statutory authority and state court interpretations; infrastructure; and historical practices.

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State agencies that regulate produced water participate in national organizations like GWPC, the Interstate Oil and Gas Compact Commission (IOGCC), and others. Through these organizations they become aware of the types of regulatory revisions and updates being made by their fellow states. Over time, states tend to make their regulatory programs more comprehensive.[15]

With the introduction of new technologies, entry into new resources areas, or the use of technologies in innovative ways, state regulatory agencies must evaluate and respond to changes in oil and gas operations to provide additional environmental and public health protection. For example, some state agencies have responded to the rapid growth of hydraulic fracturing, which has resulted in significant changes in truck traffic, industrial activity, job opportunities, leasing revenue, and water demand.

Although most oil and gas development activities are conducted safely, in some instances poor well construction, spills, leaks, accidents, and other events have resulted in produced water releases to the environment or have impacted drinking water. State agencies respond to these events by developing or modifying regulatory controls to mitigate and minimize the impacts. Each state establishes priorities on which activities are most deserving of additional controls based on state-specific concerns. Sometimes regulatory updates are done as single large efforts, while in others several rounds of incremental revision takes place.

State agencies have taken various actions to reduce or eliminate seismic impacts. Both industry and the regulatory agencies learned a great deal in a short time about earthquakes, their possible causes, and methods for mitigation.

Local residents, environmental groups, and the media have raised concerns about real or perceived risks regarding produced water management. They may contact agencies at the state and federal level and request additional controls. Although state agencies have the lead role in overseeing and regulating most oil and gas activities, federal agencies may also have a role. Solutions are often worked out on a case-by-case basis.

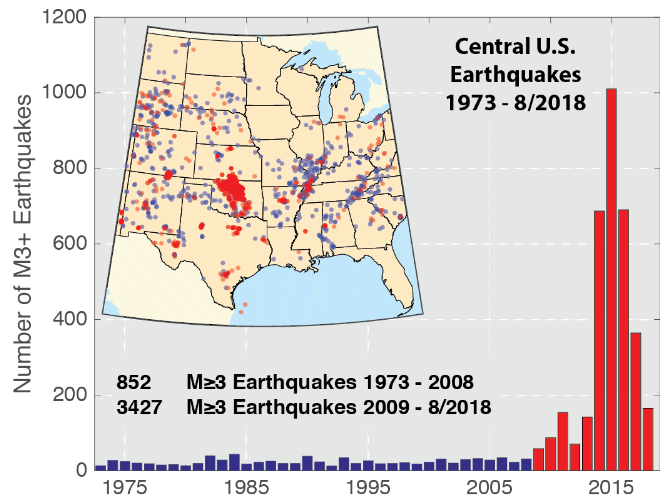

Figure 1-3. The Number of Earthquakes M 3.0 and Greater in the Central United States, 1973–8/2018

Source: USGS 2018, https://earthquake.usgs.gov/research/induced/overview.php

Although numerous disposal wells had been in operation in states like Oklahoma, Texas, Arkansas, and Ohio for decades without significant seismic impacts, a few years ago the frequency and magnitude of earthquakes increased noticeably in some areas. Figure 1-3 illustrates this increase in seismicity. Many of these earthquakes seemed to be associated with injection wells used to dispose of produced water from unconventional oil and gas development.

An example of unanticipated events that have led to a new regulatory response is an increase in seismic activity (earthquakes) associated with produced water disposal wells in parts of the country. Although numerous disposal wells had been in operation in states like Oklahoma, Texas, Arkansas, and Ohio for decades without significant seismic impacts, a few years ago the frequency and magnitude of earthquakes increased noticeably in some areas. Figure 1-3 illustrates this increase in seismicity. Many of these earthquakes seemed to be associated with injection wells used to dispose of produced water from unconventional oil and gas development. State agencies have taken various actions to reduce or eliminate seismic impacts. Both industry and the regulatory agencies learned a great deal in a short time about earthquakes, their possible causes, and methods for mitigation. GWPC took a leadership role in initiating discussions on induced seismicity related to hydraulic fracturing

15 Ground Water Protection Council, *State Oil and Natural Gas Regulations Designed to Protect Water Resources, Third Edition* (November 2017), http://www.gwpc.org/sites/default/files/State%20Regulations%20Report%202017%20Final.pdf.

Table 1-3. Regulatory Management of Produced Water by Method and Agency in Six States

State	Underground Injection Control (Class II)	Land Application	Water Discharge via NPDES	Recycling
New Mexico	NMOCD	NMDOT[1]	USEPA[2]	NMOCD
North Dakota	NDIC	NDDoH[3]	NDDoH	NDSWC
Oklahoma	OCC	OCC/ ODEQ[4]	ODEQ	
Pennsylvania	USEPA		PADEP	
Texas	TRRC	TRRC	USEPA[5]	TRRC
Wyoming	WOGCC	WOGCC[6]	WDEQ	WDEQ

Agency Acronyms
NDDoH—North Dakota Department of Health
NDIC—North Dakota Industrial Commission
NDSWC—North Dakota State Water Commission
NMDOT—New Mexico Department of Transportation
NMED—New Mexico Environment Department
NMOCD—New Mexico Oil Conservation Division
OCC—Oklahoma Corporation Commission, Oil and Gas Division
ODEQ—Oklahoma Department of Environmental Quality
PADEP—Pennsylvania Department of Environmental Protection
TCEQ—Texas Commission on Environmental Quality
TRRC—Railroad Commission of Texas
USEPA—United States Environmental Protection Agency
WOGCC—Wyoming Oil and Gas Conservation Commission
WDEQ—Wyoming Department of Environmental Quality Agency
Specific Provisions

1 The NMDOT may have jurisdiction over the use of produced water for road de-icing, http://www.emnrd.state.nm.us/OCD/education.html#OGProd4.
2 The NMED conducts compliance evaluation inspections on behalf of USEPA and reviews federal permits through certification.
3 The NDDoH has guidelines regarding use of certain produced water in dust and ice control. (NDDoH, supra Note 11)
4 The OCC regulates land application of produced water.
5 The TCEQ is not authorized to issue permits for activities associated with the exploration, development, or production of oil or gas or geothermal resources.
6 One-time land spreading on the well site is regulated by WOGCC. Other road spreading, land-spreading and land-farming operations are regulated by WDEQ and require a permit (Chapter 3 Permit Requirements for Treatment of CBM, Oil or Gas Produced Water, Wyoming Department of Environmental Quality, 7-8).

and disposal wells in 2013. As part of a joint effort with the IOGCC, the GWPC, in concert with state regulatory agencies, formed an induced seismicity work group. In 2015, this workgroup developed a primer on *Technical and Regulatory Considerations Informing Risk Management and Mitigation*, which was updated in 2017.

Examples of State Produced Water Regulations and Rights in 2017

For this report, the GWPC contracted with the Louisiana State University School of Law to evaluate how selected states regulate produced water, focusing on regulatory frameworks concerning methods of produced water management, agencies responsible for regulating these methods, and produced water ownership and liability. The states—New Mexico, North Dakota, Oklahoma, Pennsylvania, Texas, and Wyoming—were chosen based on their representativeness of a region; the geologic variability of production areas within the state; geographic, climatologic, and water need diversity; and the availability of geologic, hydrologic and water quality data. The results of this legal research are summarized below.

Regulatory Frameworks for Produced Water Management

As shown in Table 1-3, even within individual states, more than one agency may regulate the management of produced water. While underground injection control often falls under the jurisdiction of a state oil and gas agency, board, or commission, other management options such as NPDES discharge are typically regulated by either a state environmental quality agency, health agency or, in some cases, the EPA.

Such shared regulatory control may complicate produced water reuse outside of the oil and gas industry, requiring new levels of coordination between state agencies and even across state and federal agencies. This is particularly true when regulatory requirements differ substantially between multiple states that exert regulatory authority. For example, a project involving application on roadways for deicing of produced water produced in Permian basin operations would require coordination between regulating agencies in New Mexico and Texas: the NMDOT in New Mexico and the TRRC in Texas. Some agencies that may be involved in new produced water reuse options may not normally coordinate their regulatory management activities, and developing the appropriate MOUs or MOAs, etc., can take time.

Frameworks for Produced Water Rights, Ownership, and Liability

In the United States, designation and distribution of water rights are done separately by each state and in some cases tribes, interstate agencies, and compacts. While there are some general trends, each state has slightly different rules. Understanding these varying state rules and requirements is important to the oil and gas industry in obtaining water to use for drilling and fracturing fluids and in managing produced water. Table 1-4 shows the various groundwater rights doctrines and produced water ownership and liability provisions that apply in six states. Appendix 1-B provides more information on surface and groundwater rights.

Although individual state laws vary, two general doctrines apply to surface water rights: prior appropriation and reasonable use.

- Under the **prior appropriation** doctrine, the first user of the water for a beneficial reuse such as agricultural or industrial use is considered to have a right to continued use of the water. Subsequent users may utilize water from the same source but may not impinge on the original user's right to use the water.
- Under the **reasonable use** doctrine, riparian users of a water source may use water provided it does not impinge on the use of the water by other riparian users. A riparian user is defined as someone situated along the path of the water.

With respect to groundwater, states generally follow one of five common law "rules" for groundwater rights: the Absolute Dominion rule (the Absolute Ownership rule or English rule) (11 states), the Reasonable Use rule (the American rule or Rule of Reasonableness) (17 states), the Correlative Rights doctrine (five states), the Restatement (Second) of Torts rule (the Beneficial Purpose doctrine) (two states) and the Prior Appropriation doctrine (First in Time, First in Right seniority system) (13 states). However, states increasingly supplement or alter common law rules with state statutes ("regulated riparianism").

- Under the Absolute Dominion Rule (also known as the Absolute Ownership Rule), a landowner has a right to take for use or sale all the water that he can capture from below his land, regardless of the effect on wells of adjacent owners.
- The Reasonable Use Rule limits a landowner's use to beneficial uses having a reasonable relationship to the use of his overlying land.[16] As long as the use of the water is reasonable, the landowner can withdraw all the water, even to the detriment of others, without liability.
- The Correlative Rights doctrine is based on the Reasonable Use rule, but does not prohibit off-site uses and uses a proportionality rule. A landowner must limit use of groundwater to prevent interference with use of the water by adjacent landowners. The Correlative Rights doctrine does not envision an absolute right of access to groundwater or an unlimited right to pump.[17] Rather, this doctrine maintains that the authority to allocate water is held by the courts.[18] A major feature of the Correlative Rights doctrine, however, is the concept that adjoining lands can be served by a single aquifer.[19] Therefore, the judicial power to allocate water protects both the public's interest and the interests of private users.[20]

16 "Ground Water: Louisiana's Quasi-Fictional and Truly Fugacious Mineral," 44 *La. L. Rev.*, 1123, 1133 (1984).

17 Id.

18 Id.

19 Id.

20 Id.

Table 1-4. Produced Water Ownership and Liability Findings in Six States

Disclaimer: This table should not be considered a legal opinion regarding the ownership of or liability for produced water under all circumstances. It is merely a compilation of general research conducted on behalf of the GWPC.

State	Groundwater Rights Doctrine	Produced Water Ownership		Produced Water Liability	
		Operator	Landowner	Operator	Other Persons
New Mexico	Prior appropriation		X[6]	X	X
North Dakota	Prior appropriation		X[1]	X[2]	X
Oklahoma	Reasonable use	X[3]		X	
Pennsylvania	Reasonable use	[5]	[5]	X	
Texas	Absolute Ownership Rule		X	X	X[4]
Wyoming	Prior appropriation		X[1]	X	

Specific provisions that may apply to or modify the information contained in Table 1-4 include the following:

1 Water is not owned but pore space is the property of the surface rights owner.

2 Operator is immunized from liability if transferred to a commercial oilfield special waste recycling facility.

3 Produced water ownership in Oklahoma resides with the oil and gas operator except that landowners have “domestic use” of water flowing across the property. (Mack Oil Co. v. Laurence, 389 P.2d 955 (Okla. 1964)).

4 Texas limits tort liability for sellers or transferors of recycled produced water. 3 Tex. Nat. Res. Code Ann. § 122.003(a) (2015) (“Responsibility in Tort”).

5 The Pennsylvania legislature has not explicitly defined who owns produced water. As a result, produced water is likely owned by either the landowner or the oil and gas operator. However, use of groundwater off of the premises is considered unreasonable and unlawful per se if other users’ rights are interfered with. Pamela Bishop, PADEP, A Short Review of Pennsylvania Water Law, 4 (2006); R. Timothy Weston & Joel R. Burcat, Legal Aspects of Pennsylvania Water Management, in Water Resources in Pennsylvania: Availability, Quality and Management 219, 220 (Shyamal K. Majumdar et al. eds., 1990).

6 In New Mexico the term “possession” is often used because actual water ownership is by contract only.

- The Restatement of Torts rule (the Beneficial Purpose doctrine) merges the English concept of nonliability with the American standard of Reasonable Use. “The result merges prior groundwater law into a standard intended to more equitably meet growing demands on water resources.”[21]
- Under the Prior Appropriation doctrine, the first landowner to beneficially use or to divert water from a water source is granted priority of right. The quantity of groundwater a senior appropriator may withdraw may be limited based on reasonableness and beneficial purposes is used in several western states.[22]

Produced water ownership is not clearly defined and may present challenges. However, ownership varies in each state. For example, in New Mexico, there is no water right associated with produced water at the point of production. Later, if the water is used and mixed with water that has defined rights, this can change. In contrast, produced water ownership in Colorado is differentiated as being either tributary or non-tributary.

In the United States, designation and distribution of water rights are done separately by each state and in some cases tribes, interstate agencies, and compacts.

Typically, the company bringing the produced water to the surface has been responsible for its disposal. However, as produced water moves from waste to resource and potentially final disposal, ownership of the water may change.

21 Juliane Matthews, “A Modern Approach to Groundwater Allocation Disputes: Cline v. American Aggregates Corporation,” 7 *J. Energy L. & Pol’y*, 361 (1986).

22 Id.

It is important to identify how and when ownership changes occur and to understand that these changes in ownership may differ based on local or state regulations or laws. Understanding the role of water rights, mineral rights, and surface ownership in the exploration and production of oil and gas is critical in addressing the how and when there is compensation for or liability of the beneficial use of produced water.

When produced water is used within the industry for a beneficial use, liability remains with the companies. If companies provide produced water (treated or untreated) to external entities for a beneficial use, which party (company or end user) holds the liability can be less clear. For example, if an oil or gas company treats its produced water, then gives or sells the water to a rancher, the company may later be sued by the rancher if a ranch employee or a farm animal suffers ill effects.

If oil and gas companies transfer ownership of produced water to another party, the oil and gas companies assume that at least partial if not complete liability is also transferred. But this is not necessarily the case. In 2013, Texas Governor Rick Perry signed HB 2767, which partially addressed this issue. HB 2767 allowed the ownership of produced water for the purpose of treatment and reuse to be transferred from the generator (the oil and gas producer) to a person who treats for use or disposes of the produced water (a treater) and from the treater to another person who reuses the treated produced water for beneficial reuse or disposal. HB 2767 also provided some limitation for tort liability for the "treater" who later sells/gives the treated produced water to another person for use "in connection with the drilling for or production of oil or gas." The limit on liability is specific to "a consequence of the subsequent use of that treated product by the person to whom the treated product is transferred or by another person." HB 2767 does not transfer all liability, including liability to comply with TRRC regulations. In cases where produced water is sold or provided free of cost to another party, a contract may specify the party responsible for treating and monitoring the produced water, the party with ultimate responsibility for the produced water, and the point at which contractually that responsibility changes, but generally the contract will not affect a regulator's determination of liability to the state.

If a surface owner or mineral right holder expects payment for the produced water generated from oil and gas E&P, the expectation of transfer of full or partial liability if any spills or damage occurs likely exists. Additionally, entities that receive produced water for beneficial use must understand and accept the potential legal liabilities. The issues of water rights and liability were presented to a Congressional committee more than a decade ago.[23] Congress has not taken any action. Any progress on resolving these issues will likely come from state action taken to increase the likelihood of beneficially reusing produced water.

It is important to identify how and when ownership changes occur and to understand that these changes in ownership may differ based on local or state regulations or laws. Understanding the role of water rights, mineral rights, and surface ownership in the exploration and production of oil and gas is critical in addressing the how and when there is compensation for or liability of the beneficial use of produced water.

To facilitate produced water use, states may need to make statutory or regulatory changes. Texas was one of the first states to formally recognize the potential opportunities for beneficial use of produced water. For example, the TRRC, the oil and gas agency in Texas, amended its commercial and non-commercial recycling rules effective April 15, 2013[24] to remove barriers. Major rule changes encourage further conservation, reuse, and recycling of solids and liquids produced by oil and gas operators that would otherwise be considered waste. Appendix 1-C is a presentation prepared by the TRRC that describes the changes that were made. Similarly, New Mexico promulgated recycling rules to protect fresh water

23 John Veil, *Testimony*, Hearing before the U.S. House of Representatives Committee on Science and Technology, Subcommittee on Energy and Environment, regarding "Research to Improve Water-Use Efficiency and Conservation: Technologies and Practice" (Washington, DC: October 30, 2007), http://www.veilenvironmental.com/publications/pw/testimony_veil_final.pdf.

24 Texas Administrative Code, Title 16, Part 1, Chapter 3, Rule 3.8 (16 TAC § 3.8) relating to Water Protection, and 16 TAC Chapter 4, Subchapter B, relating to Commercial Recycling.

and encourage recycling of produced water. These rules became effective on March 31, 2015. Appendix 1-D details the history of the process used by New Mexico to develop its recycling rule.

Operational Standards for Produced Water Management

Not all produced water activities are subject to regulatory controls. However, they may be subject to operational standards established by the end user to meet such needs as protection of infrastructure and facilities.

For example, the quality of produced water needed as make-up water for new fracturing fluids is not subject to EPA or state water quality standards. Rather, the operator sets operational standards for specific chemical constituents to protect pumps, valves, and piping from excessive corrosion and prevent scaling, biofilm growth, and accelerated crosslinking of polymers. Companies want to ensure that the quality of water used to fracture a well is compatible with the goal of achieving the greatest possible oil and gas production.

Similarly, fluids injected into Class II disposal wells do not need to meet any regulatory standards in terms of how clean the water must be. However, the water must be a Class II fluid under the provisions of the EPA 1988 regulatory determination and cannot be altered in such a way as to make it subject to RCRA requirements. The injected water is given adequate treatment to avoid damage to the injection well and the receiving formation. The actual treatment is chosen by the operator.

In some states, when produced water is treated and used for crop irrigation, the farmer or rancher may determine the water quality standards needed to protect crops and soil structure. In other states, such as Oklahoma, specific land application standards are required by regulation. Guidelines on irrigation water quality are often available from agricultural agencies, conservation agencies or districts but these may be recommendations, not enforceable standards. These standards relate to land application of produced water rather than discharge of produced water.

Best Practices and Guidance for Produced Water Management

Companies, individually and through industry associations, have documented various best practices for managing produced water. For some activities, highly technical standards (e.g., tank construction guidelines) are available from organizations like the American Society for Testing and Materials (ASTM) and the American Petroleum Institute (API). In other cases, design and operational best practices have been developed by government agencies such as the Bureau of Land Management and other organizations.

There are a variety of resources available to the public on produced water, its regulation, best practices, etc., some of which are listed in Appendix 1-E. Also see Appendix 1-F for an example of regulatory changes in the management of produced water in the Marcellus Shale play in Pennsylvania circa 2009.

Produced Water as Part of the State Water Planning Process

As states begin evaluating long-term water needs, water planning plays an important role. More states and regions are experiencing water shortages due to drought, population shifts, and increased usage. Water plans are used to evaluate the quality, quantity, and geographic location of water versus where the water is needed. These plans may be broad in nature and cover an entire state, a watershed, or some combination.

States have various statutory, regulatory, and recommendations for water planning. Only three of the six states reviewed in the legal research referenced previously include produced water as a component in their state water plans. One possible reason for its exclusion is that produced water has not traditionally been considered a potential source of water. As treatment technology advances, populations grow, and water scarcity becomes more pronounced, the view of produced water may change over time and result in a broader look at produced water as a resource that could add to a state's water balance sheet.

Oklahoma, which has developed a comprehensive water plan for the entire state based on 13 geographic regions, considered produced water in the water planning process. The comprehensive water plan and the 13 regional reports can be viewed on the Oklahoma

Water Resources Board (OWRB) website using the following links:

- https://www.owrb.ok.gov/supply/ocwp/pdf_ocwp/WaterPlanUpdate/draftreports/OCWP%20Executive%20Rpt%20FINAL.pdf
- https://www.owrb.ok.gov/supply/ocwp/ocwp.php#regionalreports

These planning regions can use their report as a starting point to develop their own more localized water plans. The water plan(s) can be used to assess water quality or quantity or to meet some other established goal. In the case of Oklahoma, a goal was established by the legislature in a bill that became known as Water for 2060 Act.[25] This legislative action created a goal for the state to use no more fresh water in 2060 than in 2010. To achieve this goal, all water sources were considered, including brackish groundwater, produced water, and the reuse of reclaimed water from municipal or industrial processes, along with conservation methods.

In another example, the State of Kansas has completed regional water plans and included goals for effectively using produced water. In the Red Hills Regional Advisory Committee report, two of the four water goals were related to produced water and recycling in the production of oil and gas. Goal #3 is to "Reduce the amount of freshwater used in oil and gas completion operations by 4% annually" and Goal #4 is to "Work with oil and gas industry, beginning in 2040, to have 10,000 barrels a day of fresh water to be recycled from oil production for regional use in the Red Hills." More information can be found at https://kwo.ks.gov/docs/default-source/regional-advisory-committees/red-hills-rac/red-hills-rac-action-plan.pdf?sfvrsn=2.

In California, the State Water Resources Control Board (SWRCB or State Board) and the nine Regional Water Quality Control Boards (RWQCBs or Regional Boards) are responsible for the protection and, where possible, the enhancement of the quality of California's waters. The SWRCB sets statewide policy and, together with the RWQCBs, implements state and federal laws and regulations. Each of the nine Regional Boards adopts a Water Quality Control Plan, or Basin Plan, which recognizes and reflects regional differences in existing water quality, the beneficial uses of the region's ground and surface waters, and local water quality conditions and problems.[26] California's Porter-Cologne Water Quality Control Act (1969), which became Division Seven ("Water Quality") of the State Water Code, establishes the responsibilities and authorities of the nine RWQCBs (previously called Water Pollution Control Boards) and the SWRCB. The Porter Cologne Act names these Boards "... the principal State agencies with primary responsibility for the coordination and control of water quality" (Section 13001). Each Regional Board is directed to "... formulate and adopt water quality control plans for all areas within the region." A water quality control plan for the waters of an area is defined as having three components: beneficial uses which are to be protected, water quality objectives which protect those uses, and an implementation plan which accomplishes those objectives."[27] Although the current regional water plans in California do not specifically address produced water as a component of the water system for purposes of water resource planning, the regional boards process requests for produced water beneficial use and have developed a fact sheet related to the use of recycled produced water for crop irrigation.[28]

25 *Oklahoma Water for 2060 Act*; Enrolled House Bill 3055 by Steele, Lockhart and Raon of the House and Fields of the Senate; Codified in the Oklahoma State Statutes as Section 1088.11 of Title 82.

26 California Water Boards, Santa Ana Region, "The Water Quality Control Plan (Basin Plan) for the Santa Ana River Basin," (February 2008), https://www.waterboards.ca.gov/santaana/water_issues/programs/basin_plan/docs/chapter1.pdf.

27 Central Coast Regional Water Quality Control Board, "Water Quality Control Plan for the Central Coastal Basin, September 2017 Edition," California Environmental Protection Agency (September 2017), https://www.waterboards.ca.gov/centralcoast/publications_forms/publications/basin_plan/docs2017/2017_basin_plan_r3_complete.pdf.

28 California State Water Resources Control Board, "Fact Sheet: Frequently Asked Questions About Recycled Oilfield Water for Crop Irrigation" (April 5, 2016), https://www.waterboards.ca.gov/publications_forms/publications/factsheets/docs/prod_water_for_crop_irrigation.pdf.

Historically, produced water has been viewed as a waste product. With broader understanding of water volumes and the types of treatment available, produced water may become a potential resource and an integrated part of a water plan in the future. Water planning can assist states or regions in identifying where the produced water is located, the current and projected amount of produced water in the area, and the projected need for water. The ability to treat produced water to the level necessary for other uses may leave more potable water for other more restrictive uses and could be a factor in a water plan. The availability of additional water can bolster plans for economic development, increased or maintained recreation, and a more sustainable drinking water supply.

Produced water currently has limited use because of actual and perceived risk, cost of transportation, treatment and distribution, and location of the produced water versus where the water is needed, among other factors. As water becomes scarcer, the benefits of produced water use may outweigh the costs of managing, treating, storing, and transporting the water and more opportunities for produced water use may occur. Research and investigation into risks and opportunities for produced water reuse will be necessary to inform decision making, as discussed further in Module 3 of this report. Additional regulations to protect public health and the environment may apply or be developed in response to increased beneficial reuse outside the oil and gas industry.

MODULE 2

Produced Water Reuse in Unconventional Oil and Gas Operations

MODULE SUMMARY

Reuse varies by region.

Substantial differences in reuse of produced water exist based on a variety of factors both above and below the surface. For this report, data from 18 producing companies were collected on water reuse, produced water, and source water by basin. The data was aggregated by basin, or region, to determine an indicative water reuse percentage as shown in Figure 2-1. The weighted average national reuse was 10 percent but varied from 0 to 67 percent across the seven basins considered.

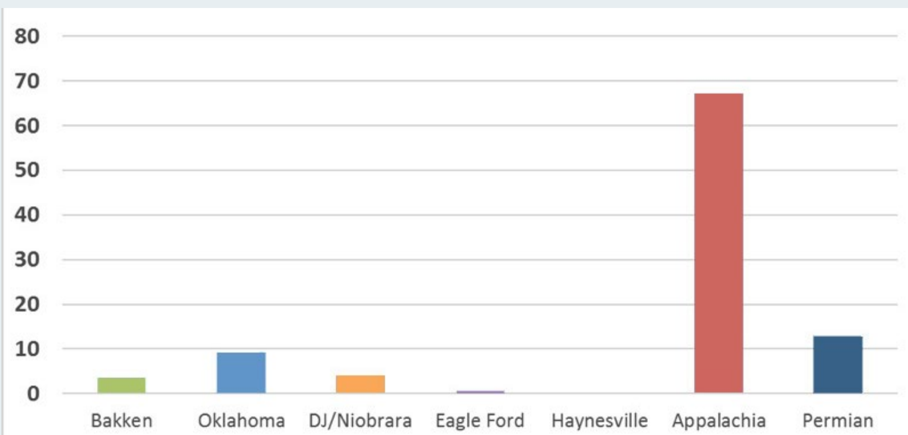

Figure 2-1: Reuse Percentage for Key Basins (18 Companies Reporting)

Source: Jacobs Engineering

Cost is the key driver of water management and reuse.

In most of the regional discussions conducted for this report, cost was the dominant driver for water reuse, although by no means the only factor companies consider. Most companies interviewed are publicly traded and have a legal obligation to conduct operations in a cost-effective way that delivers value to their stockholders. Costs were particularly emphasized with the downturn in the prices of oil and natural gas starting in 2015. Transportation costs are also a significant factor in produced water reuse evaluations.

Water management and water reuse are evolving.

Water management and water reuse are continuing to evolve in most regions. As the market demands that companies maximize efficiencies in their operations, an increasing number of companies are building pipelines for source water, pipelines to connect to disposal wells, or to other water facilities for treatment and reuse. Water management practices are also evolving in areas where local demand for source water and disposal are driving up water costs. When sourcing and disposal costs rise, reuse becomes more economically attractive and cost competitive.

MODULE 2

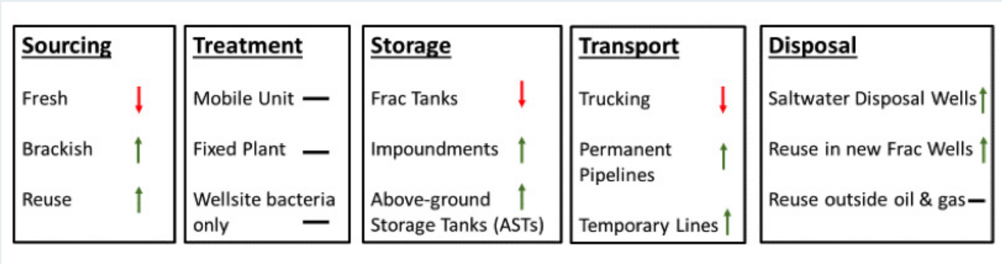

Figure 2-2: Trends in Water Management
Source: Jacobs Engineering

Companies weigh risks in water management and reuse.
Increasing water reuse can reduce company exposure to some risks but increase risk in other areas. The qualitative assessment of risks is weighed against tangible cost considerations to make water reuse plans.

Water midstream solutions are emerging.
Water midstream is a recent development involving the gathering and distribution of source water for hydraulic fracturing as well as the gathering and disposal of produced water. Although there are both positive and negative drivers for water midstream development, increasingly, third-party midstream solutions are emerging. Water midstream companies have acquired water systems and developed new projects over the last couple of years. While water midstream is generally provided by an independent company for multiple producing companies, producers are also exchanging produced water in certain situations.

> Water midstream involves the management of produced water in the field, usually by a third party, between the point of production and the point of final processing, treatment or disposal.

Data on reuse volumes is not widely available.
Neither federal regulators nor most states require reporting of the source of water used for completions, or hydraulic fracturing. Companies often report on their websites if they are reusing produced water in a specific region, but volumes are usually not reported. The *Journal of Petroleum Technology* concluded that "Improved reporting is needed to guide the industry and regulators as they look for solutions and figure out how to manage scarce resources, particularly the limited capacity of subsurface formations used for water injection."[29]

State regulation variations impact reuse practices.
Most producers and state regulators agree that states are better able to craft regulations that address regional conditions instead of applying a blanket federal regulatory framework on operations. The corollary of states having varying rules is that companies must understand all the variations for the states where they operate. If state regulators consider water reuse in crafting new and updating existing regulations, they can encourage reuse. Statutes and regulations that optimize and balance both flexibility and environmental protection will encourage reuse.

Operators should also be aware of any relevant local land use restrictions or permitting processes that may impact their ability to reuse water. This may occur at the town or county level, depending on the state.

29 Stephen Rassenfoss, "Rising Tide of Produced Water Could Pinch Permian Growth," *Journal of Petroleum Technology*, June 12, 2018, https://www.spe.org/en/jpt/jpt-article-detail/?art=4273.

Background

Managing produced water is a normal cost of doing business for oil and gas producing companies. While produced water is most commonly disposed of into permitted salt water disposal (SWD) wells within deep saline underground formations, it is also frequently reinjected into conventional reservoirs for enhanced oil recovery (EOR) operations. An additional opportunity for managing produced water is reusing it in unconventional oil and gas plays, particularly in hydraulic fracturing of wells or other well completion operations. Currently, reuse of produced water in unconventional plays is limited, primarily by cost and logistical barriers.

This module focuses on the potential for increasing the rates of produced water reuse in unconventional oil and gas operations. It addresses the evolution of produced water management and reuse practices in unconventional operations; available data on water volumes and produced water quality; operational and environmental challenges related to produced water reuse; and opportunities to facilitate water reuse through new business models as well as legislative, regulatory, policy, and research initiatives. The module also characterizes top-producing unconventional basins or regions and the similarities and differences among these basins/regions that may impact water management practices. Case studies illustrating trends in water management and reuse in the unconventional oil and gas industry are provided in Appendix 2-A.

Information for this module was gathered from public sources as well as from stakeholders specifically for this report. Research methodologies included analysis of public data and company web sites; regional discussions with groups of producing companies about water management practices; discussions with regulators, industry groups, and other non-governmental organizations; data requests to producing companies relayed through the American Petroleum Institute; and special requests to IHS Energy Group, which provides industry data on produced water and the cost of source water. Notes from discussions are included in Appendix 2-B.

Water management practices, including produced water reuse, vary substantially from region to region. All told, data on water management was gathered for this report from 18 producing companies, with operations summarized for seven of the major unconventional regions, shown in Figure 2-3. It is important to consider that, while this data set is the best available, it still represents a very small subset of the overall industry. As an indication of sample size, the 18 producing companies contributing data for this report accounted for 29 percent of the total water sourced in the seven basins in 2017.

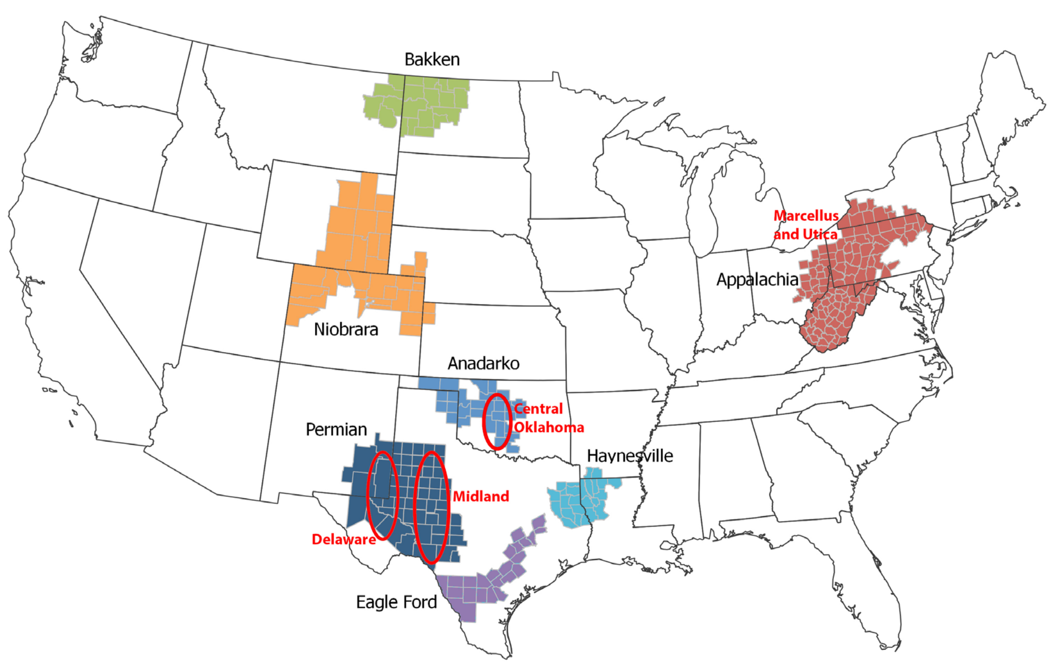

Figure 2-3: Select Oil and Gas Producing Basins/Regions in the Continental U.S.

Source: EIA https://www.eia.gov/petroleum/drilling/

This report focuses on the top seven basins/regions based on oil and gas production and current drilling activity: the Permian, Appalachian, Bakken, Niobrara, Anadarko, Haynesville, and Eagle Ford basins/regions, shown in Figure 2-3. In this report, the Permian is sometimes referred to as its component Midland and Delaware sub-basins, and the Appalachia as the Marcellus/Utica play. Central Oklahoma is a sub-basin of the Anadarko.

Water Management in Unconventional Oil and Gas Operations

This section examines the changing dynamics of water management in unconventional oil and gas operations, the potential for increasing the rate of produced water reuse in hydraulic fracturing or other well completion operations, and how this potential varies across major producing regions.

Overview of Water Management

The water lifecycle for unconventional oil and gas operations can be complex because water management practices vary widely across the United States. Figure I-5 in the Introduction charts the possible pathways for water in normal operations. The water lifecycle graphic could apply to a wellpad, an entire county, or a region. If transportation is available, the system can balance produced water with the water needed for completions more effectively. As drilling and completions move from area to area within a county or region, an integrated water system would facilitate water reuse. However, once drilling and completions activities slow down or are discontinued in a region, reuse becomes more difficult due to the distance between the location of the producing wells and the nearest completion activity.

Figure 2-4 is a simplified comparison of the infrastructure requirements for produced water disposal and reuse. The reuse graphic shows how water reuse changes the water lifecycle.

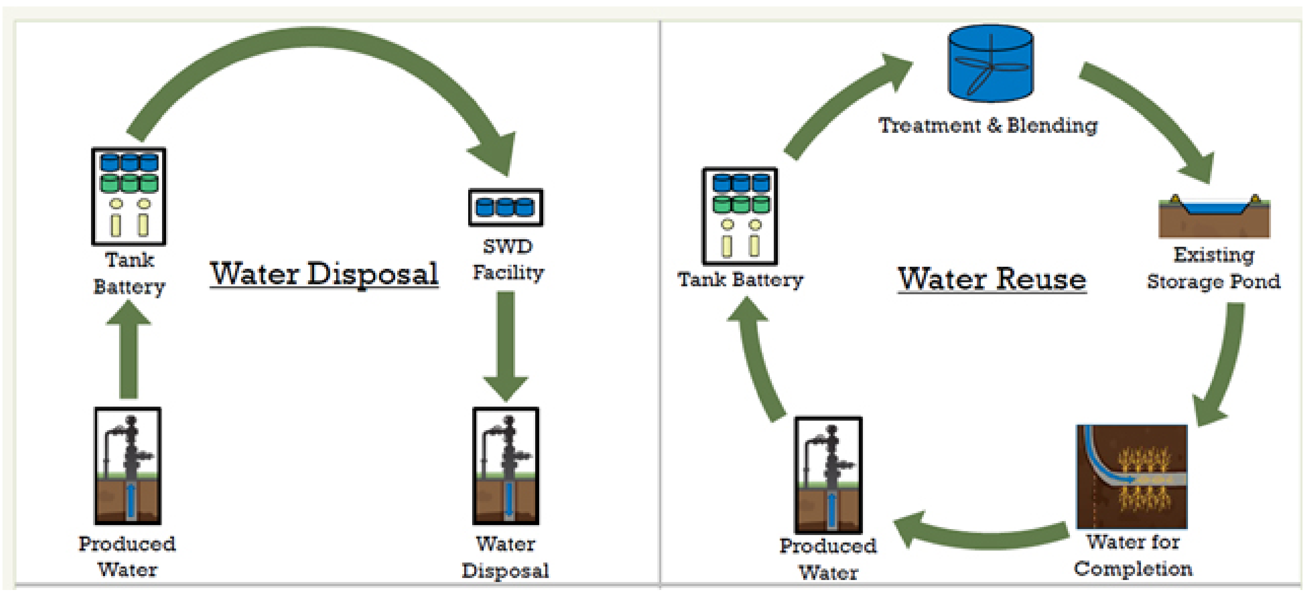

Figure 2-4: Simplified Flow Diagrams for Water Reuse vs. Disposal

Source: Pioneer Natural Resources http://investors.pxd.com/static-files/5aebb0b7-50e1-4c75-a10b-711ce71422c4

The active unconventional producing regions of the United States have substantially different water management characteristics. This variability is discussed in detail in *Water Management and Produced Water Reuse by Region*. Some areas have significant surface water available for sourcing for completions, while other areas are more arid. Water injection disposal capacity varies based on the availability of adequate geologic formations and disposal wells. When either source water or disposal capacities are limited, produced water reuse becomes more economically viable and operationally practical. The volume of water produced from an oil or gas well also varies by region and formation. These variables affect water management practices and the potential to reuse produced water.

Importantly, the reuse system must have enough storage, transportation, treatment capacity, and ongoing needs for source water, to ensure higher levels of water reuse. The logistics of transferring water from the production site to where it can be reused in another completion are critical. Often, the cost to transport water by truck can exceed the treatment and storage costs. It is usually not practical to transport water long distances by truck due to the high transport cost.[30] Storage is often needed for reuse since water production may be at a steady lower rate, but the volumes needed during hydraulic fracturing are comparatively high and intermittent. Treatment of produced water, when necessary to make it suitable for reuse, may also create residual liquids and solids that must be disposed of properly.

While it is possible to reuse produced water outside of oil and gas operations, this practice is currently limited due to the cost of treating produced water for other applications, environmental risks, regulatory restrictions, and operational factors. Produced water typically has TDS levels that are very high compared to state water quality standards for surface water bodies. If produced water discharges are allowed under an NPDES permit, the discharge will be required to meet applicable state and federal standards.[31] In most cases, treatment would be required to meet the constituent limits. Further, most potential reuse opportunities for produced water outside the oil and gas industry would require extensive treatment to lower salt content of the water. Most, though not all, produced water has at least as much salinity as seawater and commonly may have three to eight times the salinity of seawater. There are a few fields from which the produced water has a low TDS content. For example, in Texas, there are numerous fields that produce from formations with sufficiently low TDS content that the produced water can be discharged under an NPDES permit. In addition, produced water from coalbed methane (CBM) formations can be an exception to the high TDS norm. There are instances where CBM operations discharge produced water after minimal treatment due to the low salinity of the water. Produced water reuse outside of the oil and gas operations is the subject of Module 3 of this report.

Waterfloods and enhanced oil recovery (EOR) projects use produced water differently from unconventional oil and gas developments. Waterfloods have historically been performed exclusively in conventional formations, with fewer starting up in recent years. It is only in the initial years of the waterflood that makeup water is needed. Most waterfloods in the United States have reached a maturity where the produced water is reinjected back into the formation in a steady state. Figure 2-5 shows the typical water flow paths in waterfloods or EOR projects. The GWPC estimated that 45 percent of all produced water in 2012 (conventional and unconventional) was reused for EOR or waterflooding.[32] Therefore, waterfloods are independent of unconventional water management and are not likely to factor into produced water reuse for unconventional development.

30 OWRB, *Oklahoma Water for 2060 Produced Water Reuse and Recycling* (April 2017), https://www.owrb.ok.gov/2060/PWWG/pwwgfinalreport.pdf.

31 USEPA, "Oil and Gas Extraction Effluent Limitation Guidelines and Standards," 40 CFR Part 435, https://www.epa.gov/eg/oil-and-gas-extraction-effluent-guidelines.

32 John Veil, *U.S. Produced Water Volumes and Management Practices in 2012*, (Ground Water Protection Council, April 2015), http://www.veilenvironmental.com/publications/pw/final_report_CO_note.pdf.

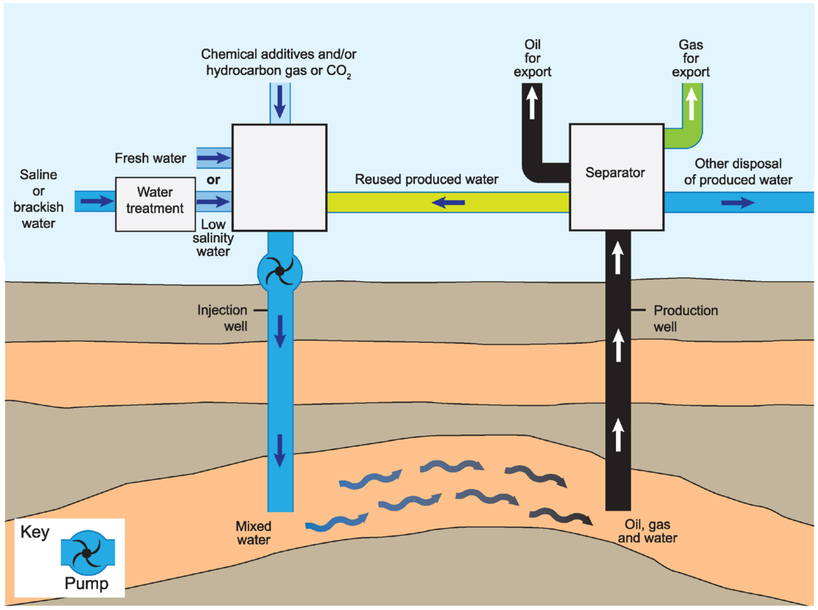

Figure 2-5: Secondary Recovery Process

Source: BP https://www.bp.com/content/dam/bp/pdf/sustainability/group-reports/BP-ESC-water-handbook.pdf

In some cases, especially in the Permian Basin and Oklahoma, conventional produced water may be available in the same region as unconventional operations. In these non-waterflood fields, it may be possible to reuse the conventional produced water as a source for hydraulic fracturing of unconventional formations.

Evolution of Water Management in Unconventional Oil and Gas Regions

Horizontal well and hydraulic fracturing technologies have had an unparalleled impact on the growth of U.S. oil and natural gas production, making it economically feasible to produce shale oil and gas resources. The multi-stage hydraulic fracturing of a single horizontal shale gas well can use an average of about 12 million gallons of water. Sourcing and managing the large quantities of water used in unconventional production is a central challenge for operators.

Currently, produced water reuse in unconventional oil and gas operations is relatively uncommon, representing about 10 percent of produced water volumes overall. However, the rate of produced water reuse and the potential for increasing it vary significantly from region to region, depending largely on the economics of reuse compared to alternatives for water sourcing and disposal.

Produced water reuse, where feasible, can play a role to meaningfully reduce the use of fresh or brackish water for unconventional oil and gas operations and reduce the need for deep injection of produced water. Reuse represents an opportunity to improve the balance of water in specific areas of the United States and to support the sustainable, economic development of important U.S. energy resources. Achieving significant levels of produced water use in unconventional producing regions will require capital investment in storage, transportation, and treatment capacity; a predictable supply of produced water; ongoing demand for source water for nearby production operations; and a supportive regulatory framework.

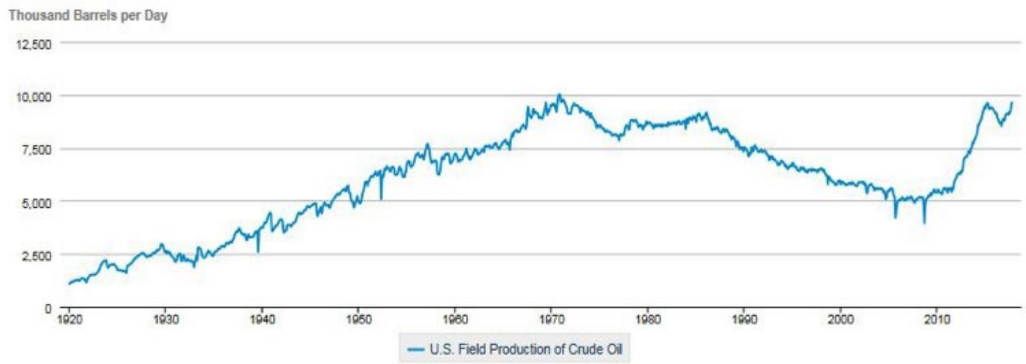

Figure 2-6: U.S. Field Production of Crude Oil

Source: U.S. Energy Information Administration (EIA)

It took roughly 25 years, from the late 1940s to the early 1970s, for oil production to increase from 5 million barrels per day to 10 million barrels per day. Over the next 35 years, production declined back to 5 million barrels per day by 2009. However, in nine years, from 2009 to 2018, oil production recovered to over 10 million barrels per day. This reversal is due to the combined technological advances in hydraulic fracturing and horizontal well development that were not economical with earlier technologies. The impact on natural gas production has been similarly significant, increasing approximately 50 percent from 2007 to 2018 (Figure 2-7).

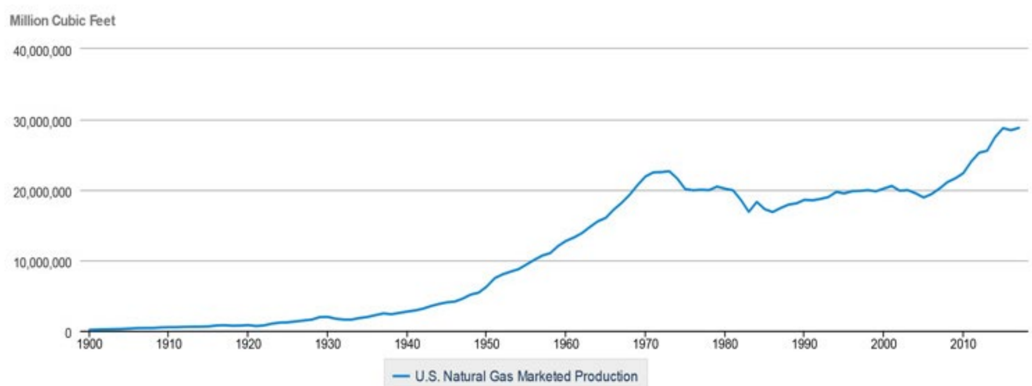

Figure 2-7: U.S. Natural Gas Marketed Production

Source: EIA

Unconventional shale development started in the Barnett Shale in the 1980s; however, significant drilling activity did not begin until gas prices increased in the late 1990s. Devon Energy acquired Mitchell Energy in 2002 and established itself as the leading producer from the Barnett Shale.*

*Texas Railroad Commission

A Decade of Change

Just as large-scale unconventional oil and gas development is relatively new, so are the practices of water planning and management within shale plays. In the early days, unconventional development required widespread, highly dispersed, and rapidly changing drilling schedules, and the priority for operators was to prove a new area would produce effectively.[33] Water planning was challenged by the limited scale of production and uncertainty over long-term drilling plans. Typically, water was sourced locally from groundwater or surface sources and, because water volumes were small compared to those used in today's hydraulic fracturing operations, there was little or no impact on local resources.

In the past decade, producing companies successfully demonstrated the technical and economic viability of hydraulic fracturing in horizontal wells. This led to a dramatic increase in unconventional production, with the U.S. horizontal rig count climbing above 900 for the first time in 2010.[34] The growing volumes of sourced and produced water required in these operations raised sustainability concerns in unconventional regions, prompting greater emphasis on long-term water planning. Stakeholders from Pennsylvania to Texas were increasingly concerned about potential groundwater contamination or use of source water for hydraulic fracturing. At the mandate from Congress, the Environmental Protection Agency (EPA) announced in March 2010 that it would conduct a research study investigating the potential impacts of hydraulic fracturing on drinking water resources.[35] In 2011 and 2012, both Texas and Oklahoma experienced extreme drought.[36] State officials and stakeholders were concerned that water use by oil and gas operations was depleting critical resources. The investor organization, Ceres, published a report in 2014 mapping unconventional development in water-stressed areas.[37]

Over time, producers began practicing water reuse in some unconventional regions to help address sourcing demand and disposal challenges. Some successful efforts to manage water more effectively are documented in the Energy Water Initiative Case Studies report from 2015.[38]

Technology developments were important in driving down costs and making such produced water reuse more feasible. Advances in hydraulic fracturing chemistry allowed operators to use produced water with minimal treatment, compared to early reuse projects.[39] In addition, drilling multiple wells from a single pad allowed water managers to better optimize water transportation infrastructure. However, the high costs of transporting produced water, particularly in areas lacking an established water pipeline infrastructure, remained a significant barrier to water reuse in most regions.

Recent Trends in Water Management and Reuse

Water management and reuse are continuing to evolve in most regions. In recent years, both the Permian Basin and Oklahoma have had rising water source and disposal costs, making reuse more economically attractive and cost competitive. Self-reporting by companies in the Permian Basin suggests that reuse has increased there in the last two years, and several producers in Oklahoma also recently announced new reuse projects. In addition, operators in the Marcellus Shale in Pennsylvania and West Virginia have pioneered large-scale water recycling technologies.[40]

Another factor driving interest in water reuse has been induced seismicity, often defined as earthquakes triggered by human activity. Induced seismicity is a concern in parts of Ohio, Arkansas, Texas, Oklahoma, and Kansas. While each situation was unique, regulators and other experts linked deep well injection of

33 Michael R. Dunkel, *Sustainability Aspects of Water Infrastructure*, SPE Paper 184445-MS, April 2017.

34 Rig Count Overview and Summary Count," Baker Hughes Rig Count, Baker Hughes, Inc., http://phx.corporate-ir.net/phoenix.zhtml?c=79687&p=irol-rigcountsoverview.

35 USEPA, *Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States, Main Report* (EPA/600/R-16/236fa), https://cfpub.epa.gov/ncea/hfstudy/recordisplay.cfm?deid=332990.

36 Bradley R. Rippey, *The U.S. Drought of 2012*, USDA, Office of the Chief Economist, World Agricultural Outlook Board (Washington D.C.: 2015).

37 Monika Freyman, *Hydraulic Fracturing & Water Stress: Water Demand by the Numbers* (CERES Report: February 2014), https://www.researchgate.net/publication/306199871_Hydraulic_Fracturing_and_Water_Stress_Water_Demand_by_the_Numbers.

38 Energy Water Initiative (EWI), *U.S. Onshore Unconventional Exploration and Production Water Management Case Studies*, prepared by CH2M HILL ENGINEERS, INC. (January 2015), https://www.anadarko.com/content/documents/apc/Responsibility/EWI_Case_Studies_Report.pdf

39 OWRB, *Oklahoma Water for 2060 Produced Water Reuse and Recycling* (April 2017), https://www.owrb.ok.gov/2060/PWWG/pwwgfinalreport.pdf.

40 "Water," Marcellus Shale Coalition™, http://marcelluscoalition.org/marcellus-shale/production-processes/water/.

produced water as the potential cause.[41] Regulatory authorities have taken a variety of risk-mitigation actions to lessen or prevent potential seismic impacts. Examples have included establishing seismic monitoring networks, installing instruments to monitor surface particle motion, suspending well operations, requiring modifications to well construction or operational parameters, requiring well tests, reducing injection pressure, or reducing water injection volumes. These actions can have the effect of increasing disposal costs and making water reuse a more economically attractive alternative.

Transportation costs have remained a major limitation on reuse in most regions. Additionally, volatility in oil and natural gas prices has constrained the ability of producers to invest in capital-intensive water systems that allow reuse. In the second half of 2014, oil prices fell from more than $100 per barrel to about $30 per barrel, slowing unconventional drilling activities and reducing producing companies' overall capital budgets. However, as oil prices recovered in 2017 and 2018, companies became more confident in planning and building water projects in order to maximize their operational efficiencies. An increasing number of companies are building temporary or permanent pipelines to transport sourced water, to connect to disposal wells, or to connect to facilities for water treatment and reuse. Such large infrastructure investments are possible due to large, contiguous acreage positions.

For example:

- **Pioneer Natural Resources** is building a pipeline network that will span 100 miles north to south and about 60 miles east to west over many of the counties in the heart of the Midland Basin (Figure 2-8). The largest water system for shale plays in the United States, the system will have line sizes up to 30- to 36-inch diameter and will distribute effluent water from municipal sources, brackish water, and treated produced water for reuse. The company was expected to spend $135 million in capital in 2018 for the Midland wastewater treatment plant upgrade, additional subsystems, produced water ponds, and produced water reuse. Pioneer is several years into the system development.[42]

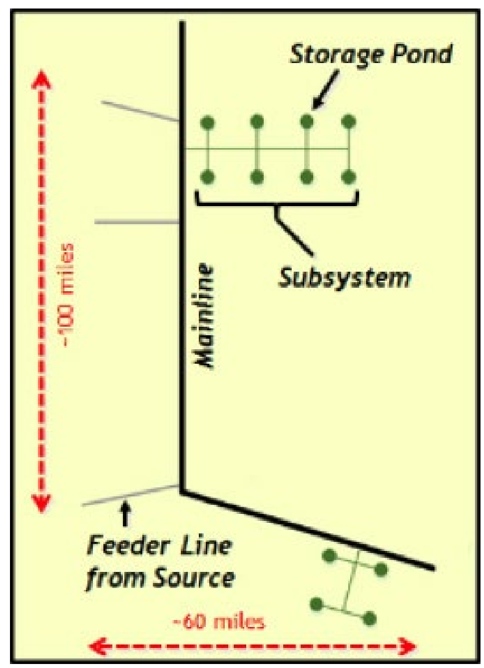

Figure 2-8: Simplified Diagram of Pioneer Water System Components
Source: Pioneer Natural Resources

Pioneer Natural Resources is constructing the largest water system for shale plays in the United States. The system will distribute effluent water from municipal sources, brackish water, and treated produced water for reuse.

41 Ground Water Protection Council and Interstate Oil and Gas Compact Commission, *Potential Injection-Induced Seismicity Associated with Oil & Gas Development: A Primer on Technical and Regulatory Considerations Informing Risk Management and Mitigation*, Second Edition (2017), http://www.gwpc.org/sites/default/files/ISWG%20Primer%20Second%20Edition%20Final%2011-17-2017.pdf.

42 Pioneer Natural Resources, JP Morgan Energy Conference, June 19, 2018.

- **Antero Resources** has the largest desalination plant for produced water reuse in the industry. The 60,000 barrels per day capacity plant in West Virginia cost approximately $500 million. The company has a water system to gather produced water and distribute the treated water for reuse (Figure 2-9).

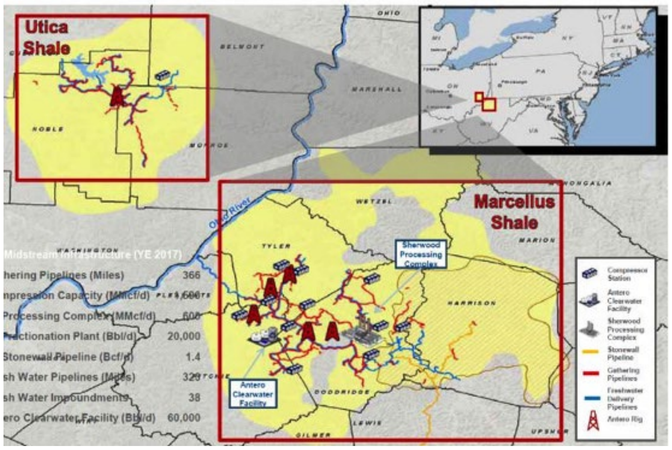

Figure 2-9: Map Showing Antero, Inc. Water Systems
Source: Antero, Inc.

This map shows the water system of Antero Resources, which operates the largest desalination plant for produced water reuse in the industry.

- **Anadarko** implemented a water recycling and closed-loop water-on-demand (WOD) system in Colorado, consisting of more than 150 miles of pipeline (Figure 2-10). The WOD system uses automation and consolidates equipment to conserve water, reduce traffic by more than 2,000 vehicles per day, and reduce greenhouse gas emissions. The system transports about 98 percent of this water via these pipelines. The WOD system has the added benefit of reducing the number of water storage tanks needed onsite, which further reduces surface impacts. Anadarko also partnered with **Western Gas**, which has a 90,000 barrels per day water system in Loving and Reeves Counties in the Delaware Basin of west Texas to enable large scale reuse of produced water.[43,44]

- In the Midland Basin, **Concho** built a 90-mile pipeline that transports more than 90 percent of its water via pipelines. The pipeline, which includes water storage facilities and can accommodate up to 125,000 barrels /day, transports treated effluent to Concho's areas of operation in the Midland Basin.

The emergence of water midstream solutions is a recent development involving efforts to coordinate water sourcing for completion operations with produced water reuse across multiple producing companies. While water midstream solutions generally are provided by an independent third-party company, producers themselves are also directly involved in exchanging produced water in certain situations. Sharing produced water among producing companies is most common in the Marcellus and Utica plays of Pennsylvania and West Virginia where operations are far from disposal wells. It has also been reported in Colorado and Oklahoma. Produced water may be transferred from a company that lacks sufficient disposal options to another nearby company that reuses the water in its completion operations. Agreements to exchange water can potentially reduce costs for both companies, while reducing truck miles driven and reducing disposal. However, if sharing of produced water triggers a commercial designation and requires additional permitting, it can be a deterrent to reuse.

43 Western Gas Partners, LP, Operations, http://www.westernmidstream.com/Operations/.

44 "Water Management," Anadarko, Inc., (2017), https://www.anadarko.com/Responsibility/Sustainable-Development/HSE/Water-Management/.

Figure 2-10: Map of Anadarko Water System in Colorado

Source: Anadarko, Inc.

Anadarko's water recycling and closed-loop water-on-demand system in Colorado consists of more than 150 miles of pipeline.

Considerations for Operators

Today, most mid and larger sized producing companies have corporate goals to reduce sourcing from fresh water, leaving more fresh water for agriculture, human consumption, aquatic life, and other industries. All 10 of the larger companies surveyed for this report had stated efforts to decrease fresh water use. (These efforts are discussed on websites for ExxonMobil, Shell, Chevron, BP, ConocoPhillips, EOG, Oxy, Anadarko, Pioneer, and Concho.) Discussions with producers' water managers confirmed this priority and identified the most commonly used non-fresh water sources as brackish surface or groundwater, produced water, and municipal wastewater effluent. In some regions, especially the Permian and Eagle Ford, brackish water is preferentially used over fresh water by many companies. Other companies in Texas and Oklahoma are sourcing brackish water when available. Areas with abundant fresh water may not be sourcing brackish water to the same extent.

Economic considerations—as outlined in the following section, Evaluating the Economics of Produced Water Reuse—are paramount in decisions made by operators in weighing reuse potential. In addition, companies weigh other relative risks and benefits of investing in produced water reuse.

Increasing water reuse can reduce company exposure to the following risks:

- Water disposal limitations caused by localized induced seismicity or over-pressuring of the disposal formation, or lack of appropriate geologic formations for disposal
- Restrictions to normal sourced water due to drought or other reasons
- Increased cost for source water and disposal capacity
- Increased trucking costs for water sourcing and disposal and other transportation restrictions
- Regulatory or stakeholder initiatives
- Reputation risks from external perceptions that the company does not support water conservation
- Missing an opportunity to shape how reuse infrastructure, technologies, and regulations develop.

Risks associated with increased water reuse may include:

- Spills associated with the additional transport and storage if required

* Upstream" refers to operations involved with the drilling, completion, and production of oil and gas wells, while "downstream" operations include refineries and gas stations. "Midstream" includes the processes of treating natural gas for sale, gas pipelines, and oil pipelines to the refineries.

- Underutilization of pipelines, storage, and treatment facilities intended for reuse as a result of decreasing oil or natural gas prices that curtail drilling plans
- Over spending on water reuse capital projects that might not be warranted by ongoing or projected future development
- Additional cost and potential liability concerns associated with storing, transporting, and treating water for reuse
- Company risks from public perception that storage, transportation, and reuse infrastructure constitute an increased footprint rather than a greener alternative
- Increased logistics challenges and costs associated with moving high salinity water through temporary infrastructure
- Concern over environmental liability in the case of produced water sharing
- Produced water ownership and custody transfer of treated produced water
- Potential formation damage from incompatible fluids
- Residuals handling and disposal from treatment system.

Recent Developments in Multi-Company Sharing and Water Midstream

Sharing produced water among producing companies is most common in the Marcellus and Utica plays of Pennsylvania and West Virginia where operations are often far from disposal wells. It has also been reported in Oklahoma. In these cases, water may be transferred from one company without enough nearby completion operations to another company needing produced water for reuse. Agreements to exchange water can potentially reduce costs for both companies, while reducing truck miles driven and water disposal. In other areas with more available disposal capacity, produced water transfers are less common. Concerns have arisen in some states about whether surface owners may make a monetary claim on water transferred among operators. A second concern is whether the liability for spills is fully passed to the receiving company. Despite these concerns, water sharing among producers has the effect of smoothing out the peaks and valleys of individual company water demands.

Another more substantial method of sharing water is the trend for midstream companies to own and operate a water system for multiple operators. The midstream ownership concept in oil and gas was developed decades ago as midstream companies developed oil pipelines and gas plants to allow the

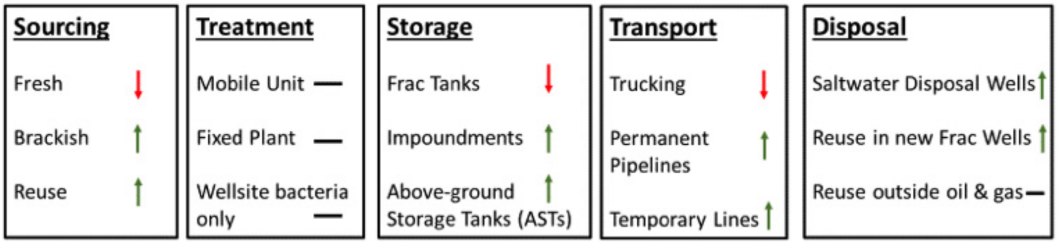

Figure 2-11: Trends in Water Management

Source: Jacobs Engineering

Figure 2-11 summarizes key trends in water management, as derived from discussions with operators for this report, and may not be accurate for all U.S. regions. Red downward arrows indicate activities that have decreased in recent years and green upward arrows indicate activities that have increased. A horizontal line indicates no clear trend.

Sourcing. Many operators have expressed a commitment to reduce fresh water sourcing. They have identified the most commonly used non-fresh water sources as brackish surface or groundwater, produced water, and municipal wastewater effluent.

Treatment. It is now widely recognized that companies do not need to remove total dissolved solids (TDS) to reuse water in oil and gas operations. Most water treatment for reuse in completions removes limited solids or a few specific constituents such as iron or scale forming cations. (In contrast, for produced water to be used outside of the oil and gas operations, most TDS must be removed, along with other constituents of concern.) The trend of using poorer quality water has reduced the level of treatment needed for produced water reuse. Most areas are using a combination of mobile treatment units and permanent plants, depending on the forecast for additional drilling and amount of the produced water to be treated.

Storage. Several states (Texas, New Mexico and Oklahoma) have been moving towards the use of larger impoundments as the scale of water operations has increased. In some cases, state regulations are more restrictive for impoundments, reducing their applicability.

Transport. Pipeline transportation of water has grown in many areas, most notably in the Permian Basin, resulting in reduced truck traffic. However, lack of a critical volume of produced water or difficult terrain reduce the feasibility of permanent water piping in some basins. For example, the Appalachian Basin has little piping of produced water, but there have been projects to install permanent piping for sourcing water. Often, temporary “layflat hose” is used to convey the water the last mile or so to the well site, where it is not usually practical to run permanent lines.

Disposal. Reuse has grown as an option to disposal in SWD wells in many areas. However, as drilling activity remains high in many areas like the Permian, it is possible that water disposal in SWD wells could continue to increase, even while reuse of produced water increases.[*]

Nationwide total withdrawals of water in the mining category, which includes oil and gas use, were about 1 percent of total withdrawals in 2015.[**] Texas’ water withdrawals in the mining category (including oil and gas) are estimated to be 1 percent of total withdrawals in 2016, the most recent data available.[†] In three states that track state-wide water use data—Colorado, New Mexico, and Wyoming—oil and natural gas activities use less than 1 percent of the total water in the state. However, the percentage of water use by oil and gas operations in some individual counties will be much higher than the state-wide average.[‡]

* Paul Wiseman, “Water, Water Everywhere in the Permian,” *The Permian Basin Petroleum Association Magazine*, May 8, 2018, https://pboilandgasmagazine.com/water-water-everywhere-in-the-permian/.

** Cheryl A. Dieter, et al., *Estimated Use of Water in the United States in 2015*, U.S. Geological Survey (USGS) Circular 1441, Supersedes USGS Open-File Report 2017-1131 (Reston, Virginia: USGS, 2018), https://pubs.usgs.gov/circ/1441/circ1441.pdf.

† Texas Water Development Board (TWRB), “Texas Water Use Estimates, 2016 Summary,” August 2018, http://www.twdb.texas.gov/waterplanning/waterusesurvey/estimates/data/2016TexasWaterUseEstimatesSummary.pdf?d=1532722565244.

‡ Western Energy Alliance, *Oil and Natural Gas Exploration and Production Water Sources and Demand Study: Colorado, Montana, New Mexico, North Dakota, Utah and Wyoming* (July 14, 2014), https://www.westernenergyalliance.org/sites/default/files/WesternWaterUseStudy.pdf.

products to move to market. Natural gas is treated near the area of production at gas plants then put into regional sales lines. Water midstream is a relatively new industry, created since unconventional oil and gas development began in select plays. Only in the last few years has water midstream begun to have significant scale. Most water midstream development has been focused in the Permian, a relatively "wet" play that continues to produce water over time.

Water midstream companies may originate from producing companies forming subsidiaries or independent companies (e.g., Pioneer, EQT, Anadarko). In other cases, they are new startups specifically focused on water midstream (e.g., WaterBridge, H2O Midstream, Solaris). Other participants include companies providing salt water disposal solutions that build gathering pipelines to expand into water midstream (e.g., Oilfield Water Logistics, Goodnight Midstream), as well as oil and gas midstream companies or other water companies that expand into water midstream (e.g., Layne Christensen, Crestwood Midstream).

Recent publicly announced projects demonstrate that water midstream solutions are poised to grow.

- **WaterBridge Resources** announced a partnership with Fort Stockton, Texas to purchase water resources for oil and gas (July 2017); acquired Arkoma Water Resources LLC with 110 miles of water pipelines (October 2017); and acquired EnWater's assets in Permian including 100 miles of pipelines and SWDs (August 2017).
- **Layne Christensen** built a 20-mile water pipeline system to water sources to deliver up to 200,000 barrels/day from their water storage facility (June 2017).

Figure 2-12: Layne Christensen's Water Storage Facility in Reeves County, Texas
Photo courtesy of Layne

- **H2O Midstream** announced the first truck-less produced water hub in Permian with pipelines, storage, and disposal (June 2018), and acquired produced water assets from Encana Oil and Gas in Permian (June 2017).
- **Solaris Midstream** acquired Vision Resources water sources and its 200+ miles of water pipelines (June 2018) to complement Solaris nearby water reuse and disposal system in southeast New Mexico; it commenced operations on the new Pecos Star System reuse system in New Mexico (May 2018).
- **EQT** (Producer) spun off its midstream company that operates Appalachian assets, including water midstream (February 2018).
- **Oilfield Water Logistics** completed a 30-mile produced water pipeline with a capacity of 150,000 barrels/day (July 2016).
- **Goodnight Midstream** added 50 miles of produced water gathering and five additional SWDs to its North Dakota water system (March 2018), which now has 24 SWDs and 250 miles of water pipelines. The company announced it is planning a 200,000 barrels/day produced water system in Lea County, New Mexico (February 2018), and that is has formed a multi-year partnership to gather and dispose produced water for producer Callon Petroleum (September 2017).
- **Waterfield Midstream**, formed with a private equity commitment of $500 million, has a focus on the Permian Basin.
- **Lagoon Water Solutions** announced backing of $500 million from private equity (September 2018) and has a focus on Oklahoma.

Pipelines can reduce variable transportation cost sufficiently to enable large-scale reuse of produced water. Yet networks built by and for a single operator may suffer from the volatility of that producer's completion schedule and produced water volumes. When larger systems are built for multiple companies, individual company's needs can be balanced more effectively. The scale of water midstream will allow reuse to grow steadily, especially in the most active areas in the Permian, Appalachia, and Oklahoma.

Table 2-1: Water Midstream Drivers
Source: Jacobs Engineering

Water Midstream Drivers	
Positives:	Negatives:
• Reduce overall costs with economics of scale	• Producer's loss of absolute control of system
• Reduce upfront capital costs for producer	• Commitment needed to Midstream to build system
• Allow producers to focus on high return completions and production	• Water mixing problems or different source quality criteria
• Allow a better overall water balance (supply and demand)	• Complexity of system allocation and working with other companies

Although there are both positive and negative drivers for water midstream development, third-party midstream solutions are increasingly emerging. Water midstream companies have acquired water systems and developed new projects in recent years.

Potential for Basin-to-Basin Produced Water Transfer

Since some formations and basins produce significantly more water than others, transferring produced water from basin to basin potentially could facilitate water reuse. For example, the Delaware Basin in Texas and New Mexico, probably the most prolific water-producing basin on a per well basis, is also one of the most active areas for drilling. This makes it more likely that Delaware Basin disposal could become restricted even if water reuse continues to grow. Meanwhile, the Midland Basin has substantial drilling and completion activity, but typically produces lower volumes of water over the life of the well than the Delaware Basin. Constructing a pipeline or series of pipelines to carry produced water from the Delaware Basin to the Midland Basin might be feasible if the Midland basin could reuse additional produced water.

A similar situation exists in Oklahoma, although at a smaller scale. The Mississippi Lime area of north central Oklahoma produces more water than can be reused and has been limited by water disposal capacity due to seismicity. The STACK play in central Oklahoma will likely need sourced water for a long time, even if it continues to ramp up water reuse. An evaluation of a 200,000 barrel per day transfer pipeline conducted as part of CH2M's water study for the Oklahoma Water Resources Board (OWRB) suggested that a pipeline could potentially be economically feasible. In a second ongoing study, OWRB is making a more in-depth review of the pipeline potential, including non-economic factors.[45] Several major uncertainties remain, including water quality differences that could increase completion costs or create formation damage in the hydraulically fractured well.

Evaluating the Economics of Produced Water Reuse

Unconventional oil and gas development is capital-intensive. An unconventional well is generally considerably more expensive to drill and complete than a conventional well due to technical factors such as the need for hydraulic fracturing. Sourcing water for the hydraulic fracturing of unconventional wells is a significant portion of the capital for drilling and completing a new well.

After the well is put on production, the management and disposal of the produced water is an operating cost that typically lasts for the life of the well. The "default" water management strategy is to source water as locally as possible and reuse it or dispose of it in nearby injection wells.

In most of the regional discussions conducted for this report, cost was the dominant driver for water reuse, although by no means the only factor companies consider. Most companies interviewed were publicly traded with a legal obligation to conduct operations in a cost-effective way that delivers value to their stockholders. Costs were particularly emphasized with the downturn in the prices of oil and natural gas starting in 2015. Within individual companies, U.S. regional operations constitute a business unit that must compete against other domestic and international business units. Not surprisingly, water managers and asset executives must demonstrate that water reuse competes economically with alternatives for that business unit.

Reusing produced water has the potential to reduce or eliminate the costs of sourcing water for well completion and of disposing of it in permitted SWD injection wells. However, decisions about water reuse involve complex determinations about both operating costs and capital investments. If low-cost

45 OWRB, *Oklahoma Water for 2060 Produced Water Reuse and Recycling* (April 2017), https://www.owrb.ok.gov/2060/PWWG/pwwgfinalreport.pdf.

sourcing and disposal are available, water reuse is not likely to be a competitive option. In contrast, if sourcing and disposal are limited and expensive, reuse may be economically attractive, provided that any necessary capital investments in transportation, storage, and treatment infrastructure can be justified. The area where reuse is highest, Pennsylvania and West Virginia, and the area where reuse is growing fastest, the Permian Basin, are regions where disposal options have been limited and disposal costs have been high or are increasing. In addition, several of the top basins are in arid regions resulting in limited availability of sourced water.

Primary water lifecycle costs for unconventional oil and gas operations can be simplified, as shown below, when produced water is not reused.

When produced water is reused, the water lifecycle cost for unconventional oil and gas operations changes (Figure 2-13). Commonly, additional sourced water is blended with reused produced water in a hybrid of Figures 2-13 and 2-14.

Comparing Lifecycle Water Costs

In evaluating the potential for produced water reuse, most operators compare the total lifecycle water costs of sourcing and disposing locally to water reuse. Comparing costs on a per-barrel basis requires considering the costs of source water acquisition, sourced water transportation, produced water transportation, produced water treatment and storage, and produced water disposal. These water cost components vary by region and even down to the individual well.

- **Sourced water acquisition.** Water source costs vary with local water availability, local and regional market demand and commercial considerations, availability of water source permits (which is more important in some states than others), water quality (fresh water and brackish water may be valued differently), and volumes purchased (larger volume contracts usually have a lower price per barrel.) Several of the top unconventional basins are in arid regions with limited availability of sourced water.

AREAS OF HIGHEST REUSE

The area where reuse is highest, Pennsylvania and West Virginia, and the area where reuse is growing fastest, the Permian Basin, are regions where disposal options have been limited and disposal costs have been high or are increasing. In addition, several of the top basins are in arid regions.

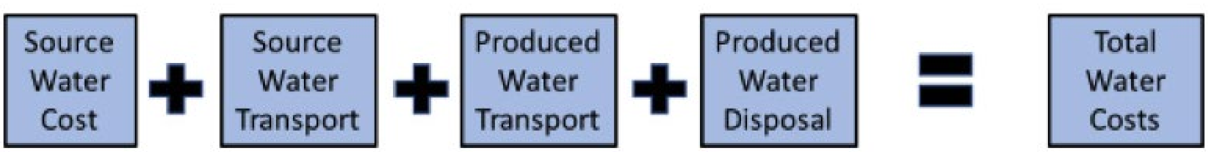

Figure 2-13: Water Lifecycle Costs without Reuse
Source: Jacobs Engineering

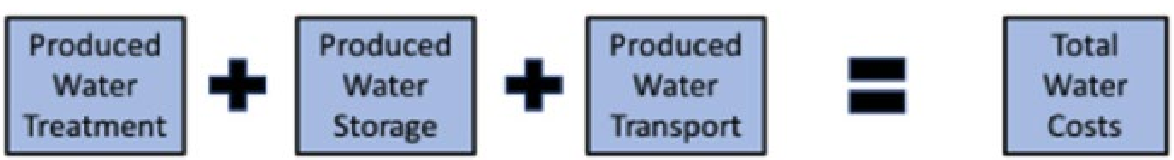

Figure 2-14: Water Lifecycle Costs with Reuse
Source: Jacobs Engineering

- **Water transportation.** Transportation costs per barrel will differ significantly depending on whether produced water is moved by trucks or pipelines. Often the most expensive component of produced water reuse, transportation can be complicated by continual changes in well locations as the drilling rig moves from well to well, and by the changing volumes of produced water, which typically decline over time as wells mature. Due to the high cost, water is rarely transported over 50 miles, so most sourcing and disposal is performed locally, normally within 10 miles.
- **Produced water treatment.** With the technical advancements in hydraulic fracturing chemistry, minimal water treatment is required for reuse within the oil and gas operations. Treatment of produced water, when necessary to make it suitable for reuse, may also create residual liquids and solids that must be disposed of properly.
- **Produced water storage.** Storage is often needed for reuse since water production may be at a steady lower rate, while the volumes needed during hydraulic fracturing are comparatively high and intermittent. Storage cost per barrel can be low if the storage system is used for large volumes of water over time. Transportation and storage costs can be reduced using on-site water treatment.
- **Produced water disposal.** Disposal costs can vary significantly by region. Costs are largely determined by the availability or scarcity of appropriate geologic formations for water disposal through injection and the number of permitted SWD wells.

Justifying Capital Investments

Water infrastructure is built in a specific area with the expectation that intensive drilling and production will follow in that location. If companies decide to discontinue drilling in the area because a new area has better performance, oil price drops make production infeasible or for any other reason, the capital invested in water pipeline, storage, and treatment facilities will be underutilized and project economics will be negatively impacted.

Before investing in the pipelines, storage, and treatment infrastructure to support produced water reuse in an area, producers need to ensure that the supply of produced water and demand for sourced water merit the investment. Considerations include produced water volumes and longevity, the concentration of development activity in the area, and the existence of nearby ongoing drilling and completions in which to reuse produced water. Unless the producing company has acreage continuity from the point of water production to the sites of reuse, landowner permission must be obtained to cross the area. Obtaining such right-of-way access takes time and resources.

Decision making is complicated by uncertainties about oil and gas prices, drilling and hydraulic fracturing forecasts in the area of concern, technology changes in completion operations, changes in regulations related to water management, and changes in

Table 2-2: Water Acquisition Costs per Barrel for Seven Counties in the Permian Basin
Source: Sourcewater https://www.sourcewater.com/

State	Data Points	County	Price High	Price Low	Price Average	Price Median	Today's Volume Median
TX	36	Reeves	$2.00	$0.30	$0.58	$0.57	50,000
TX	33	Yoakum	$1.00	$0.45	$0.77	$1.00	20,572
TX	33	Martin	$1.40	$0.35	$1.06	$0.50	8,572
TX	31	Midland	$3.00	$0.10	$0.52	$0.50	6,857
TX	14	Howard	$0.65	$0.30	$0.48	$0.48	30,000
NM	60	Lea	$1.00	$0.50	$0.80	$1.00	17,142
NM	21	Eddy	$1.25	$1.00	$1.02	$1.00	27,428

Sourcewater provided the data in Table 2-2 from their water source marketplace in July 2018, showing the asking prices for acquiring fresh and brackish water at the source in seven counties of the Permian Basin. The variation of the average cost ranges from $0.48/barrel to $1.02/barrel, over a factor of two within a single basin. The column "Today's Volume Median" is the median volume of the water offered, in barrels.

the availability of sourced water or disposal capacity and associated pricing. Typically, producing companies may only have specific well forecasts for 12 to 18 months, even if corporate financial models project drilling unspecified locations for multiple years.

Companies have indicated that a regulatory framework that reduces the cost of storage, transportation, and/or transfer costs (for example, by facilitating the use of on-site water treatment, and produced water sharing among companies operating in an area) supports increasing water reuse. Of course, all these items must be evaluated within the constraint of protecting public health and the environment.

Evaluating Water Midstream Options

The emergence of water midstream solutions may change the economics of produced water reuse for some producers. Producers may have better financial returns on producing wells than on water infrastructure, depending on the nature of the individual plays. By leveraging infrastructure investments made by water midstream companies, these producers can focus their investments on producing wells and improve their cashflows. This option allows them to respond to pressure from energy investors who encourage upstream companies to limit borrowing.

Nevertheless, producers may be reluctant to commit to a midstream solution for several reasons. First, if producing companies own and operate their own water system, they may have more control over sourcing and disposal of water. Water midstream is a developing business and the relatively new producer water teams are still figuring out this new option. Second, companies may be concerned that long-term, volume-based, take-or-pay commitments to the midstream company may be required to allow the system to be built. Third, in peak times there may be complexity with allocation of the system capacity among producers. Fourth, water mixing problems and differing water quality needs for various water sources could be an issue. Finally, regulatory and other business risks may inhibit midstream growth.

Figure 2-15: Oil Prices Since 2000

Volatile oil and gas prices have had a profound effect on unconventional drilling activity and, in turn, on water reuse investments. Leading up to the 2007 peak of oil prices, industry was just getting started with shale plays and unconventional development. The price crash of 2008 and 2009 during the great recession reminded a new generation how volatile oil prices can be. From 2010 to 2014, prices were remarkably stable, until another price collapse in 2015. In 2015 and 2016, market conditions forced numerous companies to reduce the size of their workforce and their capital budgets, which created uncertainty for longer-term planning and capital investment. As drilling levels declined in most basins, constraints on water sourcing and disposal eased, making capital investments in water projects difficult to justify.

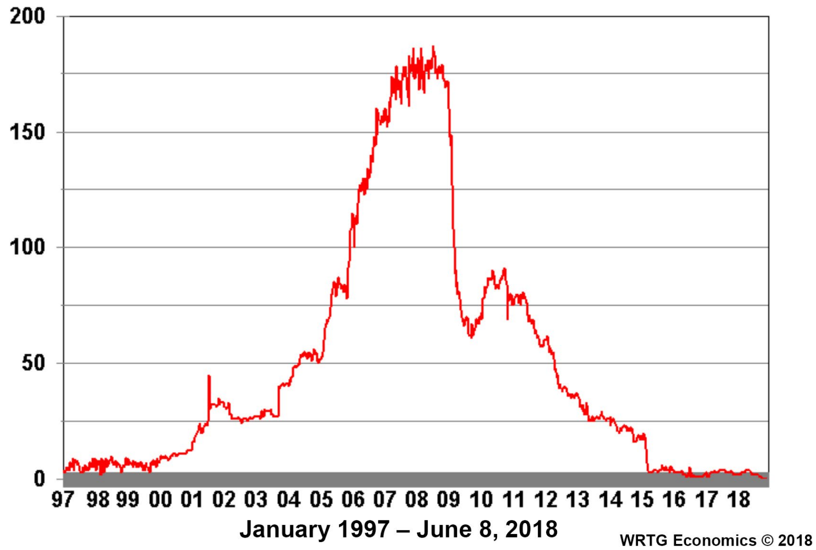

Figure 2-16: Rotary Rig Count in the Barnett Shale

Source: WTRG Economics

Rig count in the Barnett Shale, the first major region developed with horizontal wells and hydraulic fracturing, has been quite volatile. Had Barnett producers built substantial water infrastructure in peak drilling years, the infrastructure would have been largely unused. Rig count in the region has reflected not only changes in oil prices but also improving economics for other basins (Permian and Appalachia).

Operational Challenges of Produced Water Management

Operational challenges related to produced water reuse include the logistics of moving water from source to well site for use; storing produced water for reuse; regulatory and permitting requirements relative to all aspects of reuse and sourcing; landowner agreements and permissions needed, including right-of-way; and water quality requirements for completion and the need to dilute produced water.

Transporting Water for Reuse

Produced water can be transported by permanent pipelines, temporary pipelines, or trucks, or by a combination of these modes. Transportation was named by water managers interviewed for this report as the top operational challenge affecting produced water reuse.

The operating cost of moving water by existing pipelines is substantially less than the cost of trucking the water, often the difference between cents per barrel and dollars per barrel. However, if permanent pipelines do not exist, installing them typically requires companies to commit to a multi-year capital investment plan that can only be justified by the need to transport large volumes of water over an extended period of time.

The Marcellus and Utica plays in Pennsylvania, Ohio, and West Virginia are the exception to building pipelines to establish reuse. Due to regulations, hilly terrain, and the relatively small volumes of water, most water reused in Appalachia is trucked from the gathering points to the next completion site. The cost of trucking is highly dependent on the distance water must be transported, which may limit produced water reuse when the closest hydraulic fracturing site is farther away than the closest disposal well.

Permanent and Temporary Pipelines

Permanent pipelines are typically buried and are usually 18 inches or larger in diameter. Evaluations of when and where to install permanent lines to transport water must weigh uncertainties about oil and natural gas prices that impact drilling activity, capital investments, and water needs. The lead time to design, permit, and install buried water pipelines may be six to 18 months. This lag time from decision to operation is another complicating factor since drilling plans by companies are often revised monthly or even weekly.

Often, the location where the treated produced water is needed changes over time. In the simple "default" scenario, a single water line may connect a group of wells to a disposal well. However, for reuse, a complex network of water pipelines may be needed to move the water to within a few miles of the well site for reuse. Short transfers of water simplify logistics. Often, the sourced water can be conveyed with temporary surface lines while permanent water lines link produced water to disposal wells.

Designing a permanent pipeline infrastructure must take into account physical and operating conditions including normal operating pressures and flows, pipeline material, pump station spacing, and control and isolation valves. Special considerations must be given to rights of way, the crossing of roads, railroad tracks, water bodies, and environmentally sensitive areas which may require a permit. Equally important is construction oversight to ensure construction meets design specifications and addresses any required field modifications during construction. Once the pipelines are installed, monitoring of operating conditions incorporating leak detection and routine inspections is important.

In order to improve reliability of layflat hose and prevent against possible leaks, the American Petroleum Institute has a standards committee looking at this issue.

Temporary pipelines are typically laid across the surface (such as "layflat pipe" or "layflat hose") and may be smaller in diameter (4 to 12 inches) than permanent pipelines. These lines can be reliably deployed for short periods of time. Steel-reinforced (or similarly reinforced) flexible pipe is available for use as temporary pipelines. This piping is routinely available in long lengths of 600 feet or more in order to minimize connecting joints, which are a common source of pipeline leaks. Pressure ratings for temporary pipelines are well in excess of typical pipeline transfer operating pressures. More sophisticated leak detection systems are not designed for temporary pipelines. Therefore, more dependence is placed on flow and pressure monitoring and visual inspection during fluid transfer operations. In order to improve reliability of layflat hose and prevent against possible leaks, the American Petroleum Institute has a standards committee looking at this issue.

Permanent Pipelines for Water Reuse

Challenges

- High upfront capital cost
- Time required to obtain right-of-way access from landowner
- Hilly terrain and rocky soils making installation more complex and costly
- Uncertainties in oil and natural gas prices and drilling forecasts combined with the longer term payout of a water system
- Monitoring for leaks and spills and effectively responding when they occur
- Companies owning a low concentration of acreage which may lack a critical mass
- Automating pumping and storage systems where possible to ensure smooth operations and reduce labor costs
- Measuring and reporting water volumes for better transparency

Opportunities

- Lower costs to move water once the system is installed
- Potential to link storage, treatment, and disposal capacities into an efficient flexible system
- Dramatic reduction of truck traffic for water hauling and reduced accidents and road damage
- Enabling produced water reuse at a large scale
- Reducing fresh and brackish water sourcing and water disposal through increased reuse

Temporary (transfer) Pipelines for Water Reuse

Challenges

- Obtaining permits and right of way
- Infrastructure engineering and construction costs
- Monitoring and leak detection
- Routine inspection and maintenance costs
- Potential regulatory constraints

Opportunities

- Efficient movement of fluids while alleviating dependence on tracking
- Implementing robust leak detection and inspection procedures to reduce potential for leaks and spills
- Ability to quickly deploy and move the piping based on factors such as need, site conditions, etc.

Trucking

Legislators and regulators in key oil and gas producing states report hearing more complaints about truck traffic than all other industry issues. The impacts of trucking in oil and gas operations are documented in a report by The Academy of Medicine, Engineering and Science of Texas.[46] In addition to wanting to reduce impacts on stakeholders, producing companies also often want to minimize trucking due to its high costs. Yet it is unlikely that trucking can be entirely eliminated for water transport. When produced water volumes are low or the terrain is difficult, it becomes impractical to install a water pipeline. In some basins where wells are widely spaced, or the volumes of water are small, trucking the produced water is the most common transport choice (Appalachia and Eagle Ford).

Some producing companies and service companies are using GPS to track truck locations and direct them in a more efficient process. This optimization can track where the water loads should be obtained, and which nearby salt water disposal wells have the shortest wait time. The same systems can also track vehicle speed for safety purposes. These systems have aided oil and gas companies in managing their water trucking operations. For example, Pioneer Natural Resources has a sophisticated control room for water trucking operations and other logistics.[47]

TRUCKING MILEAGE MATH

Hydraulic fracturing operations at a well site may require approximately 50,000 barrels of water per day.

Trucks typically have a capacity of 120 barrels.

Thus, if a truck is making a 20-mile round trip to deliver 120 barrels of water and all of the water is delivered by truck, the trucks would drive about 8,300 miles per day.

If the loading, unloading, and roundtrip driving took two hours, the ongoing operations would require 35 trucks 24 hours per day.

For these reasons, sourced water for operations is largely provided by a series of permanent and/or temporary water pipelines.

Trucking Produced Water

Challenges

- Minimizing trucking to reduce community impacts and costs
- Consistently maintaining safe trucking operations even when industry activity is at a crescendo
- Local road conditions and weight limits
- Producer responsiblities and liabilities associated with road maintenance and repairs
- Truck fleet availability and scheduling difficulties

Opportunities

- Using technology to improve the efficiency of trucking timing and routes
- Improving methods to record and track volumes of water trucked

46 The Academy of Medicine, Engineering and Science of Texas (TAMEST), Task Force on Environmental and Community Impacts of Shale Development in Texas, "Environmental and Community Impacts of Shale Development in Texas" (Austin, Texas: TAMEST, 2017), doi:10.25238/TAMESTstf.6.2017, https://tamest.org/wp-content/uploads/2017/07/Final-Shale-Task-Force-Report.pdf.

47 Pioneer Natural Resources, Operations.

Produced Water Storage

Produced water must be stored before it is reused. This intermediate storage is needed because water normally is produced at low flow rates compared to the high, variable flow rates used during fracturing operations (up to 75,000 barrels per day). Water storage systems used in operations include frac tanks, in-ground impoundments, and above-ground storage tanks. The type selected is based on how long storage will be needed, regulations, space available, terrain, and soil/rock conditions. Measures taken during design, construction, and operations to minimize leaks and spills from storage facilities include:

- Using qualified individuals and properly designing facilities to meet specific storage needs and siting conditions
- Conducting construction oversight to ensure construction meets design specifications, addressing any required field modifications during construction
- Using spill prevention and containment at fluid loading and off-loading points
- Using secondary containment around above-ground storage (frac tanks and ASTs) with enough volume to contain a release from a potential tank failure
- Insuring proper leak detection and prevention systems for in-ground impoundments are installed and monitored appropriately.

Frac tanks

Frac tanks typically have a small capacity (450 to 500 barrels) relative to the average need of wells (180,000 to 350,000 barrels). They are used for mixing of fluids before being pumped downhole but may also be used to store water before completion. Most commonly, multiple frac tanks (six to eight) are used as buffers to supply consistent flow rates during hydraulic fracturing. Regulations in some states have restricted impoundments or make them difficult to be permitted, thus encouraging the use of frac tanks. Some regions like the Marcellus/Utica use frac tanks almost exclusively.

Figure 2-17: Frac Tanks Lined up Side by Side in Oklahoma
Photo courtesy of Chesapeake Energy

While frac tanks such as these can be moved fairly easily, they are relatively expensive to rent for the volume of water stored. The tanks can be easily inspected and leaks are easily spotted.

Figure 2-18: Covered Tank
Photo courtesy of EJS Graham ©2016

This covered frac tank is set up by layering rings of metal to the correct height and then placing the liner. Best practices would be to place the tank in a lined secondary containment area with appropriate berms or dikes to capture any leaks; regulations may require secondary containment in some states. This type of tank has a series of valves for trucks to unload into the tank. The height helps provide hydraulic head to route the produced water to nearby facilities. These constructed tanks can be moved from site to site with relative ease.

Impoundments

Impoundments are the lowest cost option for storage over a period of years. New impoundments in the Permian and Oklahoma areas may have capacities up to 1,000,000 barrels, which is 2,000 times the capacity of an individual frac tank. Most states have regulations for the design and permitting of impoundments. One of the major risks to impoundments storage of produced water is potential leaks of the liners. Most in industry consider the dual lined impoundments with leak detection a reliable way to store treated produced water that is awaiting reuse. Permitting and construction of large impoundments can take from two to 12 months or more and may require additional permitting under other regulatory programs such as dam safety.

Figure 2-19: A Pioneer Drilling Rig Behind the Lined Containment Berm of a Water Storage Pond

Source: Pioneer Natural Resources

Impoundments to store produced water are usually dual-lined with leak detection. The height of the berm, the earthen wall, may commonly be 12 feet.

Above-ground storage tanks

Above-ground storage tanks (ASTs) are often rented for short and medium time frames (months vs. years) because they can be set up quickly and easily moved to a new site. These tanks can range from 4,500 to 62,000 barrels in capacity.[48,49] They are often 10 feet tall, with steel or plastic sides and open tops, and are lined with polyethylene liners to prevent leaks. ASTs have a reduced footprint compared to frac tanks for the same water volume.

Figure 2-20: Muscle Wall Above-Ground Storage Tank in Permian

Photo courtesy of Muscle Wall Holdings, LLC

Above-ground storage tanks have a reduced footprint compared to frac tanks for the same water volume.

48 David Nightingale, Rockwater Energy Solutions, "Water Storage Issues Bring Benefits of Above-Ground Storage Tanks to Surface," *E&P Mag: Look Outside the Tank*, June 2014, http://www.rockwaterenergy.com/ep-mag-look-outside-the-tank/.

49 "Containment," Select Energy Services, http://selectenergyservices.com/content/uploads/2014/04/Containment.pdf.

Water Storage for Reuse

Challenges

- Permitting, bonding, and closure of impoundments
- Longer lead time for constructing impoundments
- Solids buildup including normally occurring radioactive material (NORM)
- Keeping costs low enough to compete against local disposal of produced water
- Preventing leaks and maintaining monitoring standards of produced water
- Preventing air emissions, especially volatile organic compounds (VOCs)

Opportunities

- Regulations that allow all types of water storage, including impoundments, as well as an effective permitting process and timeline (Example: A change in Texas impoundments rules by the Texas Railroad commission in 2013 greatly improved the adoption of large impoundments that led to additional water reuse.)*
- Reducing the difficulty for operators to share produced water and store in impoundments, whether by facilitating commercial permits or some other regulatory change

* Rick McCurdy, *Underground Injection Wells For Produced Water Disposal*, Chesapeake Energy Corporation (2011), https://www.epa.gov/sites/production/files/documents/21_McCurdy_-_UIC_Disposal_508.pdf.

Water Disposal in Injection Wells

Water disposal in injection wells has proven to be a reliable method for disposal of waste water from oil and gas operations since the 1930s. Disposal wells are typically regulated by the states under delegated authority from the EPA. Wells are designed with multiple strings of steel casing separated by cement layers to ensure that the wellbore fluids do not contaminate groundwater. Typically, produced water is injected into saline formations that were more saline than ocean water before the process started. Approximately 80 percent of the Class II injection wells are for enhanced oil recovery and the remainder are for disposal.

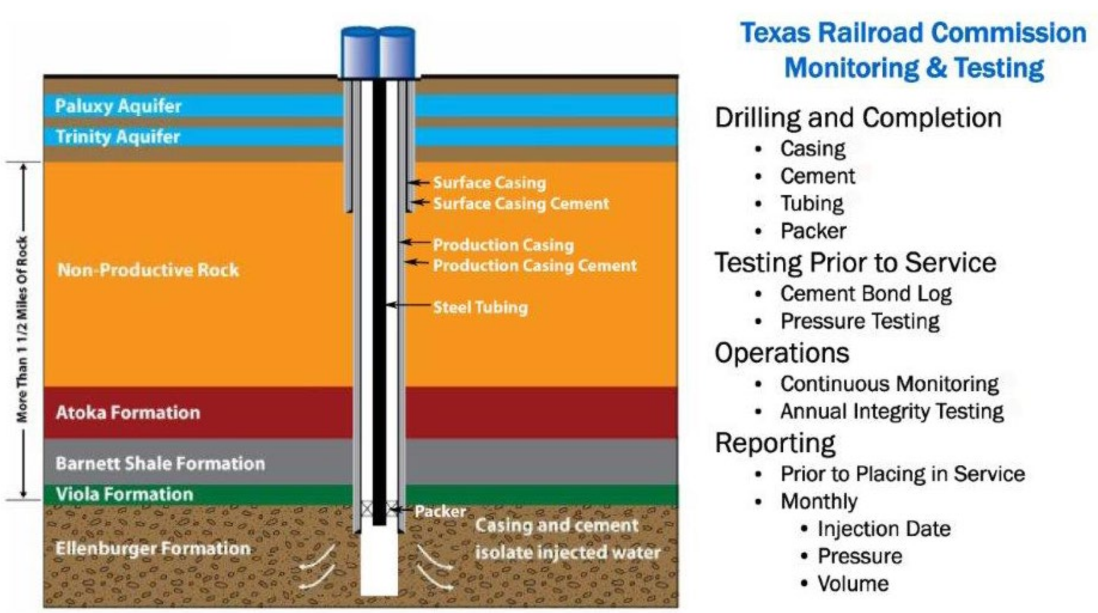

Figure 2-21: Well Monitoring and Testing Diagram

Source: After TRRC

In a typical water disposal well, thousands of feet (sometimes 10,000 or more) separate the USDWs from the disposal formation.

Discussions with water managers from producing companies indicate that having disposal capacity is a bigger concern in the Permian, Oklahoma, Haynesville, and Bakken basins/regions than in other areas. While reuse of produced water within the industry is important where possible in order to save fresh water resources, having an option to dispose is also important.

Deep Well Disposal of Produced Water

Challenges

- Having appropriate permeable formations that allow sufficient injection rates
- Knowing whether disposal in a particular area could create induced seismicity
- Increasingly difficult and complex permitting in some states and regions
- Loss of a potentially valuable water resource

Opportunities

- Complementing water reuse sytems when produced water volume exceeds what is reusable
- Allowing an outlet for produced water when reuse is impractical
- Reducing disposal to increase reuse and reduce fresh water use
- Potentially recharging pressures in depeleted formations, allowing water intended for disposal to be used for enhanced oil recovery

Treatment of Produced Water for Reuse in Hydraulic Fracturing

Prior to about 2010 or 2011, most reused produced water for hydraulic fracturing was treated to reduce total dissolved solids (TDS) to a fresh level. This desalination was necessary because hydraulic fracture chemistries in use at the time required high quality water to create a highly viscous gel to carry the sand to formation. In 2004, Devon Energy established the first commercial reuse in the Barnett Shale using desalinated produced water.[50,51]

The Energy Water Initiative report in 2015 documented a trend toward more robust hydraulic fracturing chemistry allowing the use of lower quality water with high salinity.[52] Today, most reused produced water is minimally treated due to these advances in fracture fluid chemistry. This minimal approach—which treats only a few specific constituents to create "clean brine"— is significantly less costly than desalination. The most common items treated are bacteria, total suspended solids, iron, and a few other constituents. In some cases, only bacteria are treated.

Desalination

In limited cases, desalination is still done to provide an option that could meet discharge water quality requirements or reduce the potential risk from a spill. Companies using this treatment include Antero, Eureka, and Fairmont. Southwestern Energy had a desalination facility in its Fayetteville Shale operations, but that site is not currently treating produced water. Desalination of high salinity produced water tends to be very expensive and creates substantial solid waste that requires disposal. For example, a 20,000 barrel per day desalination plant processing 150,000 mg/L TDS brine could produce approximately 350 tons per day of solids.

The technology and operational efficiency of water treatment in oil and gas operations has improved markedly over the last 10 years. These improvements have helped facilitate the economic reuse of produced water in more situations by reducing costs for a variety of clean brine and desalination treatments.

50 "Water," Devon Energy, https://www.devonenergy.com/sustainability/environment.

51 "History," Fountain Quail Energy Services, https://www.fountainquail.com/our-company/history.

52 EWI, *U.S. Onshore Unconventional Exploration and Production Water Management Case Studies*, prepared by CH2M HILL ENGINEERS, INC. (January 2015), https://www.anadarko.com/content/documents/apc/Responsibility/EWI_Case_Studies_Report.pdf.

A related trend has been the development of permanent plants to sell some of the separated solids such as salt, calcium chloride, and iodine. The revenue from selling separated material has also helped offset treatment costs.[53,54]

One of the challenges to water treatment costs has been the lack of consistently available large volumes of water. Smaller volumes of water, less than 5,000 to 10,000 barrels per day, have fewer barrels over which to spread the fixed costs. The economies of large-scale systems that transport and treat large volumes of water (perhaps 50,000 barrels per day and up) offer lower costs per barrel. As the water pipeline infrastructure projects grow larger, the economies of scale should continue to reduce treatment costs.

Desalination Treatment of Produced Water

Challenges

- Reducing water treatment costs for smaller volumes of water
- Finding methods to dramatically reduce costs as pipeline systems aggregate larger volumes of water
- Determining the optimal blend of permanent plants and mobile treatment facilities to meet changing water volumes and pace of activity
- Developing sustainable water agreements to align with typical pace and changes in operational activity (i.e., ability to commit to plants without having committed water volumes)
- Managing treatment solids and residuals, including potential NORM and TENORM constituents, that pose regulatory and disposal challenges
- Regulatory constraints or prohibitions on discharge of treated produced water
- Ambiguous ownership of produced water in some states

Opportunities

- Reducing energy requirements to operate treatment facilities
- Improving separation of saleable solids such as salts and calcium chloride
- Finding effective methods to treat scale and other challenges associated with mixing different quality water sources
- Optimizing water quality for reuse
- Demonstrating that commercially viable treatment technologies can treat to discharge standards
- Resource preservation

53 Rick McCurdy, Chesapeake Energy Corporation, *Produced Water Treatment–A Look at Current Technologies, Challenges and Opportunities*, U.S. Department of Energy, Advanced Manufacturing Office (July 10, 2017), https://www.energy.gov/sites/prod/files/2017/08/f35/2017%20-%20Jul%20-%20AMO%20Clean%20Water%20-%20McCurdy.pdf.

54 Rick McCurdy, Chesapeake Energy Corporation, "Treating Produced Water for Beneficial Use–Current Challenges and Potential Future Advances," Ground Water Protection Council 2016 UIC Conference (2016), http://www.gwpc.org/sites/default/files/event-sessions/McCurdy_Rick.pdf.

Enhanced evaporation

As an alternative to water reuse or SWD disposal, natural evaporation has been used to reduce produced water volumes in limited cases. The method is most widely reported in Wyoming (seven companies), followed by Colorado (four companies), Utah (four companies), and New Mexico (three companies). Disposal costs using enhanced evaporation ranged from $0.40 to $3.95 per barrel.[55] Using natural evaporation to reduce produced water disposal has generally not been effective because the rate of evaporation from a large impoundment is small compared to the amount of produced water. Natural evaporation is more cost effective in arid to semi-arid conditions. Ponds should be kept shallow as evaporation occurs only at the surface.

Some treatment companies offer enhanced evaporation as an alternative to desalination and discharge. A 2017 survey found costs to be 39 to 54 percent of desalination costs.[56] Enhanced evaporation may be most feasible when disposal and reuse are already fully employed. If the choice is between desalination and evaporation, evaporation may have more positives in some situations.

Figure 2-22: Evaporator
Photo courtesy of Logic-ES

Evaporation technologies range from thermal treatment to spraying pretreated water in the air in a contained area.

Enhanced Evaporation of Produced Water

Challenges

- Typically more costly than disposal if available
- Disposing of significant volumes of solids (unless evaporation is done simply to concentrate brine for disposal)
- Minimizing the risk of salt in evaporated steam (critical to local soil conditions)
- Need for quick startup (in months) when rigs and completions are restricted due to oil or gas price pullback
- Air emissions and emission control processes
- Lack of direct reuse opportunity

Opportunities

- Competitive costs (may be roughly half cost of desalination)
- Less rigorous permitting criteria and no water quality criteria for discharge
- Potential for new efficiencies as technologies and operations progress with more regular operations
- Reduced disposal volumes

55 National Energy Technology Laboratory, Fact Sheet–Offsite Commercial Disposal, https://netl.doe.gov/node/3179.

56 OWRB, *Oklahoma Water for 2060 Produced Water Reuse and Recycling* (April 2017), https://www.owrb.ok.gov/2060/PWWG/pwwgfinalreport.pdf.

Environmental Challenges of Produced Water Management

The production, transport, storage, reuse, and disposal of produced water involves environmental risk. Because of its high saline content and other constituents, produced water can create numerous potential environmental impacts if it contacts soil or water bodies, including impacts on ecosystems and wildlife. In comparison to disposal options, reuse requires storing produced water in greater volumes for longer periods of time and transporting it from points of generation to the well site and in some instances to treatment facilities between the two. As water transfers increase, so do the risks of spills. Other potential environmental impacts can result from mismanagement of residuals generated from produced water treatment as well as air emissions.

Upstream oil and gas operations are typically regulated by several federal and state agencies, including state departments of environmental quality or natural resources or, in cases of federal or tribal lands, the Bureau of Land Management.

Managing the environmental challenges of produced water management requires minimizing and remediating spills and leaks, managing residuals, controlling air emissions, and taking actions to protect wildlife.

Minimizing Spills and Leaks

Surface spills and well casing leaks near the surface are the most likely pathways for oil and gas activities to contaminate drinking water sources and cause environmental damage. The depth separation between oil-bearing zones and drinking water-bearing zones in many areas makes direct fracturing into drinking water zones unlikely.

Methods of minimizing leaks and spills vary by the types of storage and transportation used.

- **Storage.** Key elements for surface impoundments may include double lining with leak detection and freeboard requirements, while for ASTs they are secondary containment, leak detection and overfill control, and fluid loading and off-loading operations to catch and retain potential spills.
- **Permanent pipeline infrastructure.** Permanent pipelines require appropriate design, considering physical and operating conditions including normal operating pressures and flows, pipeline material, pump station spacing, and control and isolation valves. Special considerations must be given to the crossing of roads, water courses, and environmentally sensitive areas. Equally important is construction oversight to ensure that construction meets design specifications and addresses any required field modifications during construction. Isolation valves are recommended on either end of a water or road crossing and at the boundaries of environmentally sensitive areas to allow the isolation and depressurization of these pipe segments in the event of a leak. Additionally, isolation valves should be located at defined distances along pipe segments. Leak detection for pipelines can be accomplished in many ways. A reliable standard method involves monitoring of pressure and flow and comparing the results to a system model of what pressures should be. Routine visual inspection of the pipeline route and right-of-way are likely to catch small leaks that the system monitoring may not find. In addition, continuous monitoring leak detection systems provide relatively quick and accurate identification of a leak and its location. These systems include negative pressure wave, real-time transient model, and statistical corrected volume balance.[57]
- **Temporary pipeline infrastructure.** The primary method of minimizing leaks and spills is routine inspection of the lines.

The design and construction of an impoundment, tank, or pipeline is a project encompassing not just design by qualified individuals but oversight and quality assurance during construction. Design plans and specifications should be developed and may need to be sealed by a professional engineer. However, that is not where the involvement of design personnel ends. Construction oversight by qualified individuals must also occur during construction.

57 Tina Olivero, "Drastically Reducing Pipeline Oil Spills," *OGM™* (Our Great Minds Online Magazine: 2017), https://theogm.com/2018/05/16/drastically-reducing-pipeline-oil-spills/.

This oversight will include documenting all field modifications to address conditions encountered that were not accounted for during design, checking field modifications against design parameters and getting sign-off by the designer if needed, verifying field quality control requirements are met, and developing final as-built plans documenting the facility as it was constructed.

An effective way to ensure proper construction oversight is by developing and implementing a Construction Quality Assurance (CQA) plan. A formal CQA establishes procedures to document that construction is in accordance with the approved engineering plans and specifications and meets appropriate regulatory requirements. It also provides a paper trail to verify that specified activities are properly completed. Verification is achieved through a CQA report documenting the extent to which construction was performed in compliance with design drawings and specifications.

Ongoing inspection and maintenance are required throughout the course of operating impoundments, tanks, or pipelines. Elements include routine inspection, the use of remote sensing technology, and a program to correct identified issues and verify repairs are completed properly. A checklist is an effective tool in both conducting and documenting this effort. For in-ground impoundments, inspections of the berms and liners are important. For steel tanks, corrosion monitoring is appropriate.

At the end of a facility's service life, any impacts from operation must be addressed (starting with identification and followed by remediation and verification of completeness of any response action). Tools and programs will be different but typically include a level of financial assurance to provide for future closure/decommissioning costs.

Remediating Spills

Oil and gas produced water is often much saltier than sea water and can damage soil if large amounts spill or leak during storage or transport. In fact, a produced water spill can cause much more long-term damage to land than an oil spill. Various studies of reported spills of produced water indicate that the majority are small spills. The typical small spill may have limited impact and can be remediated a variety of ways. These small spills can however persist for decades and rarely naturally remediate, primarily as a result of the high salinity that impacts both vegetation and soil structure. Remediation of the brine impacts typically includes flushing of the soil to reduce the salt content in the plant root zone and rebuild the soil structure (addressing the cation and anion imbalance), and revegetation to re-establish the ecosystem and counter erosion. Revegetation can take multiple years, depending on severity of the spill.

Beyond salt, produced water can contain many chemicals[58] that are either present in formation water or known to be used in the well completion or maintenance processes. Chemicals may range from ethylene glycol (antifreeze) to hydrochloric acid and could include radionuclides (from NORM). Regulator-approved chemical detection methods only exist for about a quarter of the potential chemicals.[59]

Minimizing and Remediating Spills

Challenges

- Minimizing large and small spills in all aspects of water management and reuse
- Developing cleanup standards and remediation techniques for various environmental media (surface water, ground water, drinking water, soil, pad materials, wetlands and other environments) for a variety of spill types including produced water

Opportunities

- Limit risk and impact of water spills using automation and leak detection technologies
- Limit risk and impact of water spills using proper design and operating practices in containment and transport

58 Karl Oetjen, Colorado School Mines, "Emerging analytical methods for the characterization and quantification of organic contaminants in flowback and produced water," *Trends in Environmental Analytical Chemistry 15* (2017), 12–23.

59 Dan Mueller, "Water Management Associated with Oil and Gas Development and Production," *EM*, August 2017, http://blogs.edf.org/energyexchange/files/2017/09/emaug17.pdf.

Residuals Management

The most common residuals with minimally treated produced water are suspended solids that may be separated in the treatment process or settle in the water storage impoundments or tanks. These solids must be disposed of according to state regulations. Often the solids will be sent to landfills. If the solids contain NORM that is concentrated through industrial processes, they may be classified as "technologically enhanced naturally occurring radioactive material" (TENORM) and must be disposed of in hazardous waste landfills designed for such materials. Management of the solids creates an additional cost to the reuse process and may introduce separate risks. Typically, the residuals may contain salts that will potentially create risks to groundwater if they leak from the landfill. Transporting any elevated concentrations of NORM or TENORM from the treatment site to the special landfill also introduces potential risks. In some cases, residual solids may have a marketable value that can help offset the costs of treatment. However, it sometimes is not clear who owns these saleable solids.

In some treatment processes, a residual concentrated brine may be produced. This brine would normally be disposed in a disposal well. The disposal of concentrated brine can reduce the volume of solids needing disposal.

Residuals Management

Challenges

- Designing processes that limit solid waste
- Handling solids appropriately and preventing environmental impacts from residuals
- Being particularly cautious with NORM and TENORM management and disposal, which is becoming an increasingly regulated aspect of oil and gas operations

Opportunities

- Selling marketable products from residuals when possible to offset treatment costs

Managing Air Emissions

Air emissions from produced water in tons per year would vary depending on what type of storage is being used and the throughput that storage can accommodate. Some produced water could be transported to a large impoundment in volumes that result in permit/notice triggering levels of volatile organic compounds (VOCs) being released. Emissions must be managed in accordance with state and federal regulations. For example, methanol is a common additive in hydraulic fracturing and production operations. It is considered a VOC. Methanol emissions from water impoundments have been an issue infrequently. One conclusion of a whitepaper examining the use of methanol in hydraulic fracturing was that "Because of methanol's low tendency to volatilize out of water and into air, methanol will practically not volatize from flowback ponds."[60] However, since methanol has a boiling point much lower than water, thermally enhanced evaporation or distillation processes will allow methanol to volatize before water vapor, which may require that it be trapped or scrubbed from the emissions.

Water treatment, especially desalination, may involve heating produced water with natural gas. The burned natural gas will increase CO_2 emissions and may increase emissions of other gasses such as sulfur dioxide (SOx) and nitrogen dioxide (NOx), which may change permitting criteria for a facility.

Hydrogen sulfide (H_2S) is naturally present in some producing formations or can be a byproduct from bacteria growth in stored produced water, especially during hotter months. The amount generated from an impoundment is typically low, but H_2S is a potential safety and health concern if concentrated. Low levels of H_2S can create a bad smell and a nuisance. Most producing companies have established operations to prevent H_2S growth in impoundments, including relatively simple methods of circulating the water and aerating the ponds. Additionally, there are mechanical and chemical methods available to remove higher levels of H_2S from water.

Air Emissions Management

Challenges

- Preventing VOCs, H_2S or other air emissions that could create any risk to health or safety
- Effectively monitoring air emissions from water reuse operations

Opportunity

- Establishing water reuse operations and systems that minimize air emissions and keep overall emissions from upstream energy operations as low as possible

60 Tarek Saba, et al., "White Paper: Methanol Use in Hydraulic Fracturing Fluids" (Methanol Institute: Alexandria, Virginia, January 20, 2012), http://www.methanol.org/wp-content/uploads/2016/06/White-Paper-Methanol-Use-in-Hydraulic-Fracturing-Jan-11.pdf.

Preventing Potential Impacts to Wildlife

State and federal regulations apply to protect wildlife around oil and gas operations. Federal statutes, such as the Migratory Bird Treaty Act,[61] provide substantial penalties for the death of many species of birds that could occur from contact with oil in an open top tank or impoundment. Some states require bird abatement for produced water storage. Common forms of prevention may involve netting or a sound source to prevent birds from landing. Netting is not typically practical for large impoundments.

Figure 2-23: Netting over Impoundment

Photo courtesy of American Netting, LLC

Netting can be used over open tanks or impoundments to prevent birds from landing.

It is important to keep animals from being trapped in an impoundment due to a slippery liner. Often, fences around the impoundment secure the area and protect walking wildlife. Companies also want to prevent deer and cattle from walking on the liner, since their hooves may puncture the liner and trigger the leak detection system.

Protecting Wildlife

Challenges

- Preventing any occurance of wildlife impact over the long life of an oil and gas development
- Deterring birds from produced water impoundments and tanks, which may be attractive to them as water sources
- Preventing trucking hazards to deer and other wildlife

Opportunities

- Building water pipeline systems that can have less impact on wildlife than trucking
- Protecting and enjoying wildlife

61 *Migratory Bird Treaty Act of 1918* (16 U.S.C. 703-712; Ch. 128; July 3, 1918; 40 Stat. 755) as amended by: Chapter 634; June 20, 1936; 49 Stat. 1556; P.L. 86-732; September 8, 1960; 74 Stat. 866; P.L. 90-578; October 17, 1968; 82 Stat. 1118; P.L. 91-135; December 5, 1969; 83 Stat. 282; P.L. 93-300; June 1, 1974; 88 Stat. 190; P.L. 95-616; November 8, 1978; 92 Stat. 3111; P.L. 99-645; November 10, 1986; 100 Stat. 3590 and P.L. 105-312; October 30, 1998; 112 Stat. 2956 https://www.fws.gov/laws/lawsdigest/migtrea.html.

Regulatory and Legal Challenges and Opportunities

Management of produced water is subject to a complex set of federal, state, and sometimes local regulations that may address a wide range of topics (permitting, siting criteria, bonding, water acquisition, temporary storage alternatives, facility construction, facility operations, liabilities for misuse, discharge reporting and response, environmental monitoring transport, infrastructure, land disturbance, reclamation, treatment technologies, beneficial use, recycling, reporting site closure, and decommissioning). The purpose of state and federal regulations is to allow for orderly and efficient development of resources while ensuring protection of the environment, public health, and safety.

Regulations evolve over time in response to such factors as emerging practices, new technologies, and identified risks that are not adequately addressed by existing regulations. In the case of produced water management, the emergence of unconventional resource development has led to new midstream approaches to water gathering, storage, treatment, and distribution for use. These midstream operations are often outside of traditional state regulatory frameworks and require state authorization and oversight for activities that are neither associated with permitted oil and gas operations, nor facilities at Class II underground injection operations. For example, the surface storage of produced water may entail the use of impoundments, which may be regulated by a state agency other than the state oil and gas agency. Determining how these impoundments would be regulated and by which state agency or agencies will require a thorough review of current statutes and authorities. State laws typically establish broad performance objectives and empower one or more state agencies to promulgate more specific regulatory standards, with authority to enter properties and enforce state standards. This process will need to be repeated with respect to midstream water management companies and will take time. In the meantime, rapid growth of such companies could lead to potential problems for which no or only a limited regulatory response is available.

In response to the emergence of a midstream produced water industry, some state legislative bodies have passed laws to authorize these emerging practices. For example, in 2014, the Ohio General Assembly enacted Am. Substitute House Bill 59, authorizing the Ohio Division of Oil and Gas Resources Management to develop new rules to establish requirements for permitting and operating new facilities that will temporarily store, recycle, treat, and/or process produced water not associated with sites permitted for drilling and completion of oil and gas wells or Class II injection wells. By law, Ohio now authorizes new facilities by permit until such time that rules are enacted.

In recent years, some states have enacted rules that address specific components of the challenges posed by emerging practices. For example, prior to 2013, Texas producers were having difficulty obtaining permits for impoundments to store produced water to facilitate reuse. The issue was often just the difference in time to obtain a permit as compared to the fast-changing drilling plans. The Railroad Commission of Texas changed the requirements for permitting to allow permits by rule under certain conditions. The revised Statewide Rule 8 (16 Tex. Admin. Code §3.8) allowed companies to implement water reuse impoundments in a timelier fashion and reuse has grown over time.

The Ground Water Protection Council and Interstate Oil and Gas Compact Commission can facilitate the exchange of applied research, emerging standards, and continually improving regulations to assist states in developing and implementing effective regulatory frameworks. The State Oil and Gas Regulatory Exchange program provides a process for the exchange of ideas as state regulations evolve.

The Oklahoma Corporation Commission (OCC) has revised bonding requirements associated with storage impoundments to support produced water reuse. This bonding provides the state with the funds necessary to close any water impoundments left behind in the event of a bankruptcy. In this regard, the Oklahoma Corporation Commission (OCC) requires bonding on a per barrel of water storage capacity at a water treatment facility. The trend in water storage is to construct impoundments to accommodate the larger hydraulic fracturing completions being performed. Typically, multiple impoundments will be necessary to effectively reuse produced water in a service area of a recycling facility, potentially leading to multi-millions of dollars of bonding requirements in a relatively small play area. This bonding requirement has been identified by producing companies as a potential deterrent to produced water reuse. The OCC has been working cooperatively with industry on this issue so as not to discourage recycling of produced water, while at the same time remaining environmentally protective. The OCC will review new application bonding requirements on a case-by-case basis with an eye toward potential use of blanket bonding for multiple recycling facilities by producers.

Most producers and state regulators agree that states are better able to craft regulations that address regional conditions instead of applying a blanket federal regulatory framework on operations. The corollary of states having varying rules is that companies must understand all the variations for the states where they operate. Statutes and regulations that optimize and balance both flexibility and environmental protection will encourage reuse. Where reuse of produced water is important to an individual state, evaluating the differences between its laws and regulations with those of similarly situated states might result in changes that could encourage reuse.

The Case for Improved Reporting

Neither federal regulators nor most states require reporting of the source of the water used for completions or hydraulic fracturing. Companies often report on their websites if they are reusing produced water in a specific region. Most states require that operators report water volumes and chemicals used during hydraulic fracturing in their FracFocus® reports by well. It is not a requirement to report the source or the quality of the water used, which may be surface water, groundwater, treated wastewater effluent or produced water (reuse).

State regulators continually balance the need for data to evaluate compliance with the risk of increasing operating costs and potentially reducing economic activity. The lack of full information about reuse frequency and produced water availability will limit policymakers' understanding of the issue when it may become more important. For example, in the event of a drought or disposal problem, regulators may have a limited ability to determine how important reuse could be in helping with a potential solution.

> **INFORMATION IS CRITICAL**
>
> The lack of full information about reuse frequency and produced water availability will limit policymakers' understanding of the issue when it may become more important.

Produced water reuse is a relatively new priority in this fast developing and changing industry. The *Journal of Petroleum Technology* concluded that "Improved reporting is needed to guide the industry and regulators as they look for solutions and figure out how to manage scarce resources, particularly the limited capacity of subsurface formations used for water injection."[62]

62 Stephen Rassenfoss, "Rising Tide of Produced Water Could Pinch Permian Growth," *Journal of Petroleum Technology*, June 12, 2018, https://www.spe.org/en/jpt/jpt-article-detail/?art=4273.

Research Needed to Facilitate Produced Water Reuse

Most producing companies interviewed for this report do not see significant research needs or opportunities related to water reuse within oil and gas operations. Breakthroughs in water transport, a major operational and cost barrier to reuse, are viewed as unlikely, since pipelines and pumps for produced water are mature technologies. However, the interviews identified the following areas as potentially valuable.

- **Leak detection**. Optimization of leak detection is potentially promising. Monitoring systems for real-time detection of leaks in saltwater pipelines flag pressure changes that are inconsistent with the rate of pumping. This technology for large high-rate saltwater systems is immature and research may help improve operational efficiencies. More sophistication with controls from the impoundments and pumping may also be beneficial.
- **Addressing specific water treatment challenges**. Some producing companies identified water treatment as an area where technology improvements could potentially be very beneficial. They noted that, while service providers have already substantially reduced water treatment costs in recent years, technical challenges are periodically encountered due to unique water quality or mixing. Problems may relate to scale buildup or a specific analyte such as barium, sulfate, iron, or some other component. Research by universities and water treatment companies to improve solutions for specific treatment problems could help reduce costs for reuse and increase reuse volumes.
- **Improvement in enhanced evaporation or desalination**. Advances in enhanced evaporation technologies could be beneficial in reducing the risk of salt carry over into the steam or spray. Also, enhanced evaporation or desalination that concentrates the brine to near saturation without creating solids would reduce the potential impact of managing large amounts of solids in landfills.
- **Automation in treatment systems**. Research on treatment systems that can be operated remotely with little or no human intervention offer the potential for labor cost savings.
- **Separation of saleable products during treatment**. Water treatment costs can be partially offset when treatment companies separate out saleable products. Analytes such as iodine or lithium may be separated when in higher concentrations, even without full desalination of the produced water. For example, Iofina —a company involved in the exploration and production of iodine, iodine specialty chemical derivatives, and produced water and natural gas—is separating iodine found in higher-than-normal concentrations in the produced water of one Oklahoma operator. Research could further the separation of saleable products by determining the best saleable products, and processes to create the products.
- **Water treatment research needs**. Companies also touched on water treatment research needed to facilitate water reuse outside the oil and gas industry through discharge or use in another industry. To date, the discharge of produced water has been rare, hindered by the high costs of required desalination and other treatments. Yet, from an operational perspective, some producers contend that discharge may need to be integrated into long-term water management strategies, especially in plays with limited disposal compared to the volume of produced water (e.g., the Marcellus in Pennsylvania, the STACK in Oklahoma, and the Delaware Basin in New Mexico and Texas). Discharge also might be built into water planning for periods when drilling and completion activities drop. In those periods, the same water network that normally moves water to where it is needed for reuse within the oil and gas industry could transport it to a desalination treatment facility that allows the water to be used in another industry or discharged. Research into automation, low energy treatment options, and low-cost capital facilities will be important.

Another potential route to offsetting costs is the separation of saleable products during treatment processes. Separation of products has even more potential when treating for discharge rather than for reuse in the oil and gas industry, since desalination is involved. Research is needed to determine what useful products can be created and which processes are best to create the materials. Module 3 discusses this further.

- **Regulatory changes needed to facilitate discharge**. Enabling the surface discharge of appropriately treated produced water will require regulatory changes, which may include modifications to storage requirements, NPDES discharge permitting, transportation requirements, and others.

> **REGULATORY UPDATE NEEDS**
>
> Enabling the surface discharge of appropriately treated produced water will require regulatory changes, which may include modifications to storage requirements, NPDES discharge permitting, transportation requirements, and others.

Policy Initiatives to Facilitate Reuse

Producers interviewed for this report raised several consistent themes when discussing how state and local policies may support or inhibit increased water reuse.

- **Tracking water transfers**. Regulators in some areas of the Marcellus/Utica region could facilitate reuse by reducing requirements to track produced water moved from site to site by actual barrels. The barrels cannot be definitively tracked when they are mixed together in storage.
- **Commercial designation**. In some states, water management requirements for non-commercial reuse are more flexible than for commercial reuse. While the commercial regulations usually set a higher standard, sometimes they prevent companies from working together efficiently to reuse produced water. With the trend toward larger reuse systems and water sharing, regulations should be reviewed to assure they strike the right balance between resource protection and reuse
- **Storage**. Companies want the flexibility to use the best operational option for the situation. In some cases, states limit or prohibit impoundments for storing treated produced water. In many situations, the alternate produced water storage options are substantially more expensive and deter reuse.
- **Temporary layflat lines**. If temporary layflat hose is not permitted to transport produced water the last mile or two to the well site, the alternatives are less feasible. Trucking water for the last short run or running permanent pipe to every well site may increase costs dramatically and increase the impacts related to truck traffic.
- **Right-of-way on county roads**. Right-of-way on county roads can enable water transport via permanent or temporary pipelines. Water reuse is hampered in counties that prohibit this possibility.
- **Timely permitting**. If operators encounter lengthy permit approval times for reuse operations, they will tend to default to local sourcing and disposal to meet completion schedules. Speeding up approval times will support greater water reuse. Some companies have been critical of the historically slow process of obtaining an NPDES permit to discharge produced water, reporting that in some cases it can take two years, which is much longer than the companies' well planning cycle. It should be noted that there are many reasons why the permitting process may take longer than expected including insufficient program funding, problems with the application, communication and response time-lags, and others. Also, Bureau of Land Management (BLM) water-related permitting processes are reportedly much slower than state processes.
- **Clarity of regulations**. Companies mentioned that variation of rules from state to state can complicate their efforts to understand and comply with the intentions of the regulations.

- **Incentives**. Some companies mentioned that incentives such as state or federal tax deductions for water reuse would be helpful. However, any incentives should consider possible unintended consequences and the associated administrative effort to implement the plan.
- **Produced water ownership**. Companies cite ambiguity related to produced water ownership as a potential impediment to produced water sharing and reuse. In some states, they report it is not clear that the producer can sell or transfer water to another producer. In most basins, produced water does not have any value if one tries to sell it. If it has value, it is often less than the cost to treat and transfer the water. In some instances, surface owners may claim a right to a royalty to any water that is treated and sold.

Water Management and Produced Water Reuse by Region

Water management practices, including produced water reuse, vary substantially from region to region. This section focuses on the top seven basins/regions based on oil and gas production and current drilling activity: the Permian, Appalachian, Bakken, Niobrara, Anadarko, Haynesville, and Eagle Ford basins/regions, shown in Figure 2-24. In this report, the Permian is sometimes referred to as its component Midland and Delaware sub-basins, and the Appalachia as the Marcellus/Utica play. Central Oklahoma is a sub-basin in the Anadarko.

Overview of Regional Differences

Significant variables affect water management across these regions. Some have appropriate geology for water disposal and wide availability of permitted underground injection control (UIC) wells, while others have very limited access to disposal. Some areas have abundant supplies of surface water or groundwater, while others are relatively arid. Some are primarily rural regions, others more urban. The amount of produced water from a typical well varies by region, as does the quality of the produced water. Differences in topography determine the feasibility and cost effectiveness of developing water pipeline systems. Applicable state and local regulations vary by region, as do landowner and mineral lease requirements relating to the use of water. Some regions are affected by potential seismicity concerns associated with disposal well injection into specific formations.

Currently, the Appalachia basin with its Marcellus and Utica formations of Pennsylvania and West Virginia has the highest rate of produced water reuse. Primary drivers for the Appalachian region's reuse have been the extremely limited number of regionally available disposal wells and the high costs of transporting water to these distant wells. Pennsylvania has less than 10 permitted disposal wells for produced water; in comparison, Texas has over 8,000 permitted and operating disposal wells.[63,64]

The second highest level of reuse is occurring in the Permian Basin of west Texas and New Mexico. Despite its large disposal capacity, the Permian Basin has had significant increases in reuse projects over the last two years, driven by rising costs for other source water and increasing costs for disposal injection wells due to high demand.

Figures 2-25 to 2-41 highlight the relative production of the top basins and contrast differences in their water use and management.

63 "Injection and Disposal Wells," Railroad Commission of Texas (RRC), http://www.rrc.state.tx.us/about-us/resource-center/faqs/oil-gas-faqs/faq-injection-and-disposal-wells/.

64 Rick McCurdy, *Underground Injection Wells For Produced Water Disposal*, Chesapeake Energy Corporation (2011), https://www.epa.gov/sites/production/files/documents/21_McCurdy_-_UIC_Disposal_508.pdf.

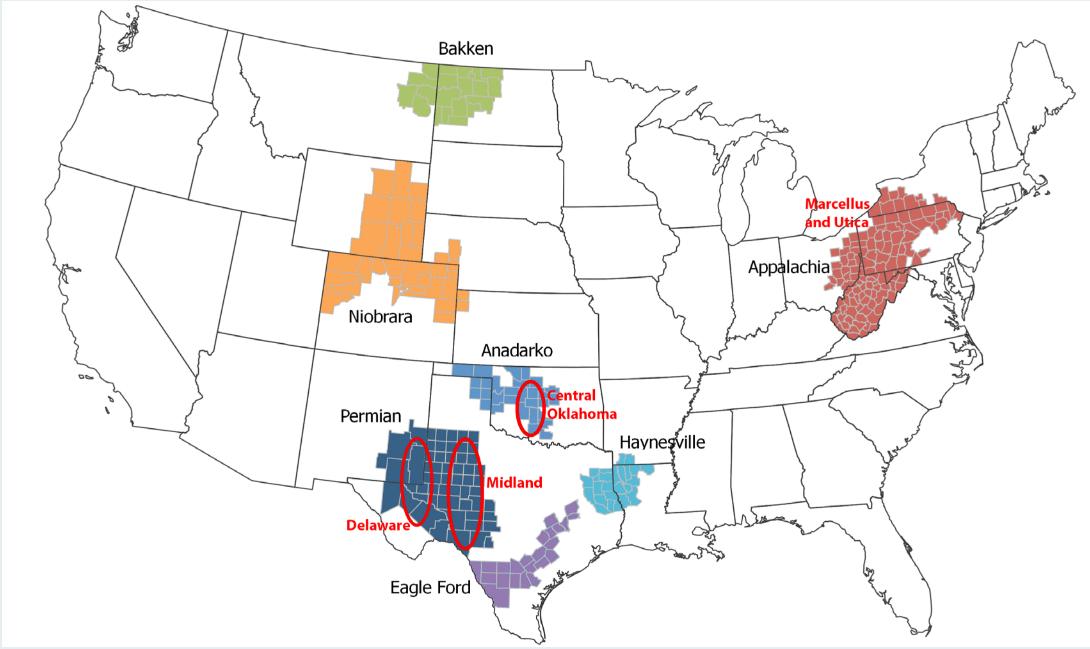

Figure 2-24: Select Oil and Gas Producing Basins/Regions in the Continental U.S.
Source: EIA https://www.eia.gov/petroleum/drilling/

The top seven basins/regions based on oil and gas production and current drilling activity are the Permian, Appalachian, Bakken, Niobrara, Anadarko (includes Central Oklahoma), Haynesville, and Eagle Ford.

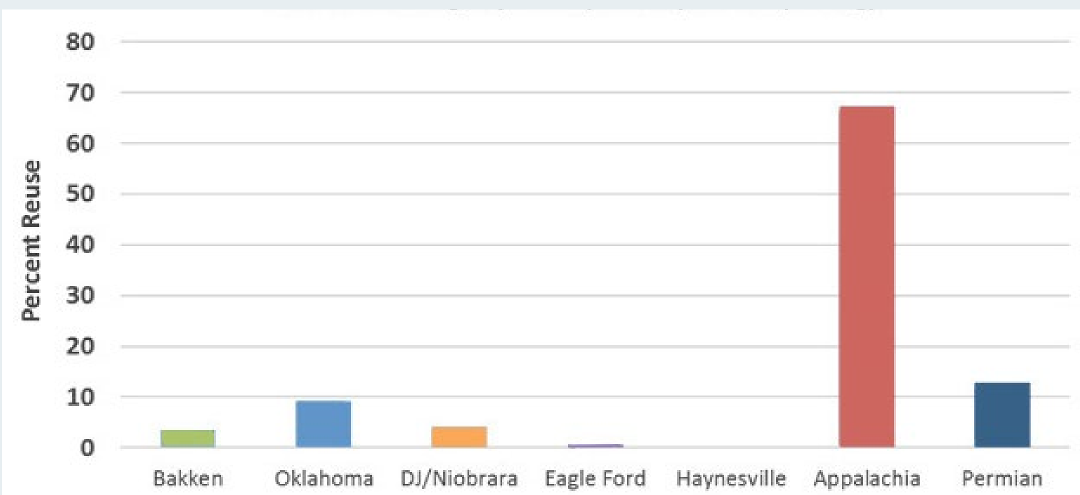

Figure 2-25: Reuse Percentage for Key Basins (18 Companies Reporting)
Source: Jacobs Engineering

Produced water reuse is highest in the Appalachia and Permian Basins. This figure is based on data collected for this report from 18 producing companies and aggregated by basin/region with help from the American Petroleum Institute. The weighted average reuse was 10 percent but varied from 0 to 67 percent across the seven basins considered. The reuse volume was divided by the lower of the water sourced or water produced in the basin. The sourced water was higher than the produced water in four of seven basins. The 18 producing companies contributing data for this report accounted for 29 percent of the total water sourced in the seven basins in 2017.

Top Producing Basins

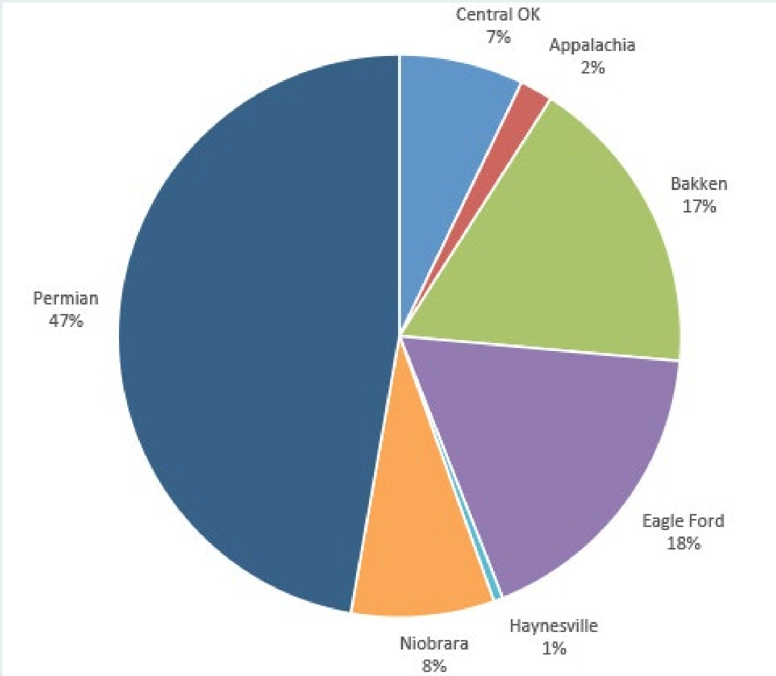

Figure 2-26: U.S. Onshore Oil Production by Basin December 2018

Source: After EIA

The Permian is the leading onshore oil-producing basin, followed by Eagle Ford and Bakken.

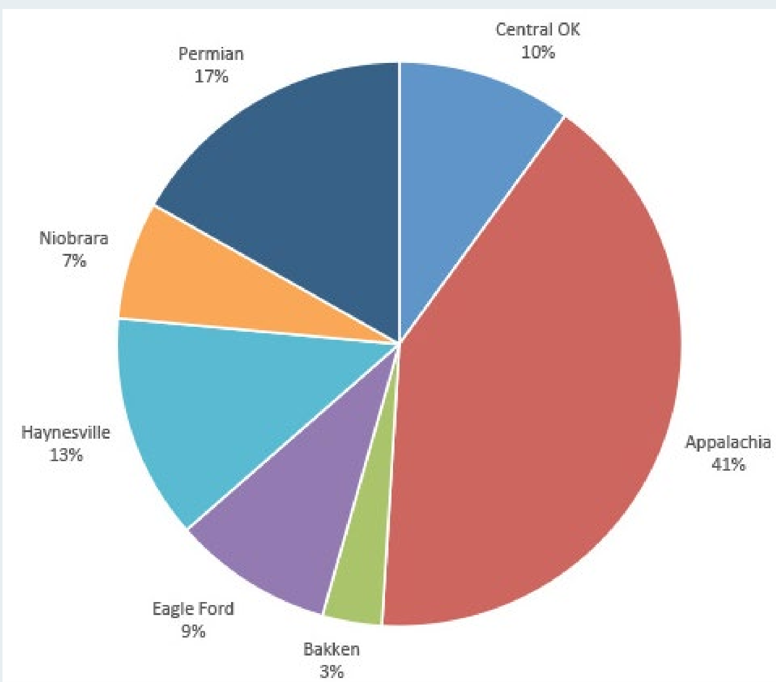

Figure 2-27: U.S. Onshore Natural Gas Production by Basin December 2018

Source: After EIA

In natural gas production, the Appalachia is the leading basin, followed by Permian and Haynesville. Generally, the higher the oil or gas production, the more drilling and well completions have occurred. Higher activity will correlate to higher water source demands and, to some extent, to produced water production rates. Higher activity may also correlate to higher produced water reuse opportunities.

Trends in Production for Leading U.S. Basins

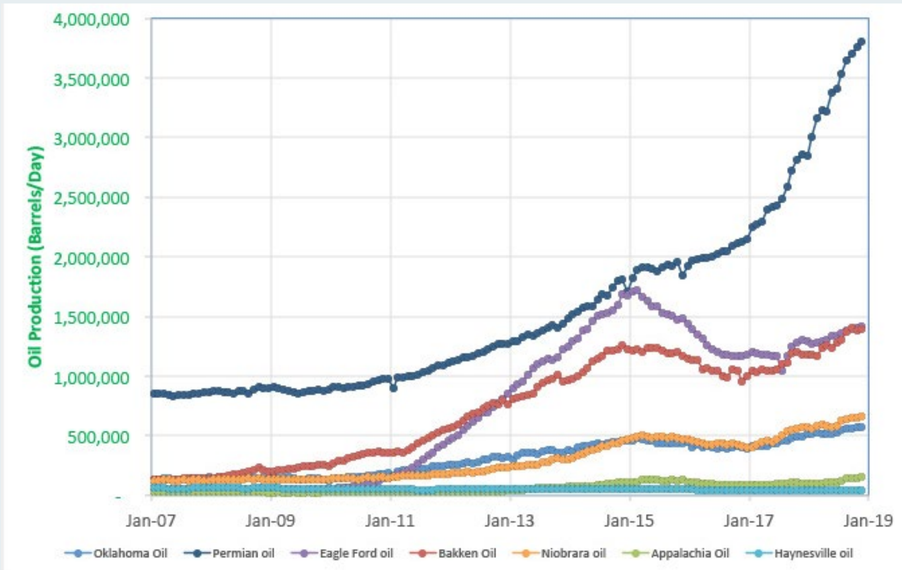

Figure 2-28: Oil Production for Major Basins/Regions
Source: After EIA

Well completion activity and oil production growth rates have varied over time based on changing technical understandings of the economic viability of the basins. Oil production in the Permian was high in 2007 from conventional production. The Bakken grew faster than the other areas from 2007 to 2011. The Eagle Ford production grew dramatically from 2011 to 2015. The Permian Basin is the only oil producing basin that continued to grow when oil prices fell in late 2014 and early 2015. Production dipped in the other basins, then resumed a growth trend around January 2017 as oil prices recovered.

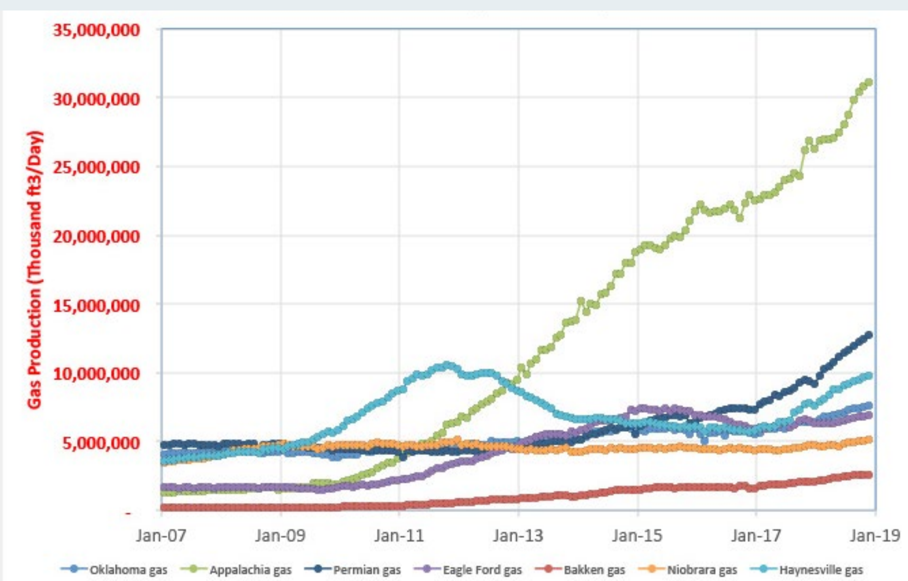

Figure 2-29: Natural Gas Production for Major Basins/Regions
Source: After EIA

Natural gas production has grown dramatically in Appalachia, driven by high-rate well production and proximity to the East Coast gas market. The other basins resumed their increasing production trend starting around January 2017. The Appalachia and Haynesville areas are the only pure gas plays. The others are primarily oil plays with associated gas that is produced with the oil.

Rig Counts Across Major Basins

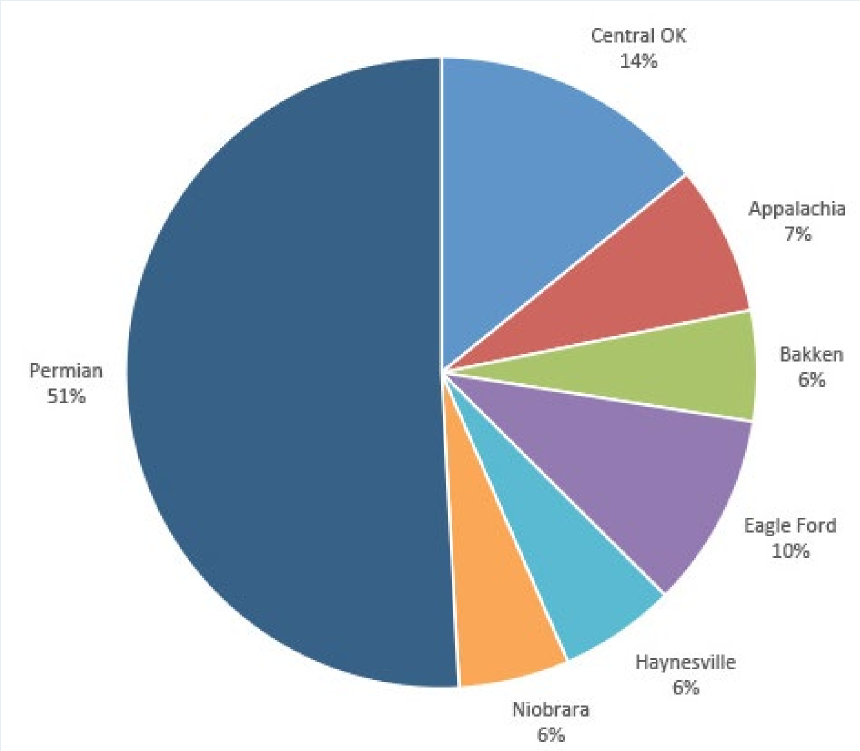

Figure 2-30: U.S. Onshore Rig Count by Basin December 2018

Source: EIA

The Permian basin had just over half of the U.S. onshore rigs in December 2018. High rig count is an indicator of a region's having economically viable wells and foretells potential production growth. Higher rig counts increase demand for sourced water for hydraulic fracturing which, in turn, will eventually lead to higher water production.

Distribution of Water Use for Hydraulic Fracturing

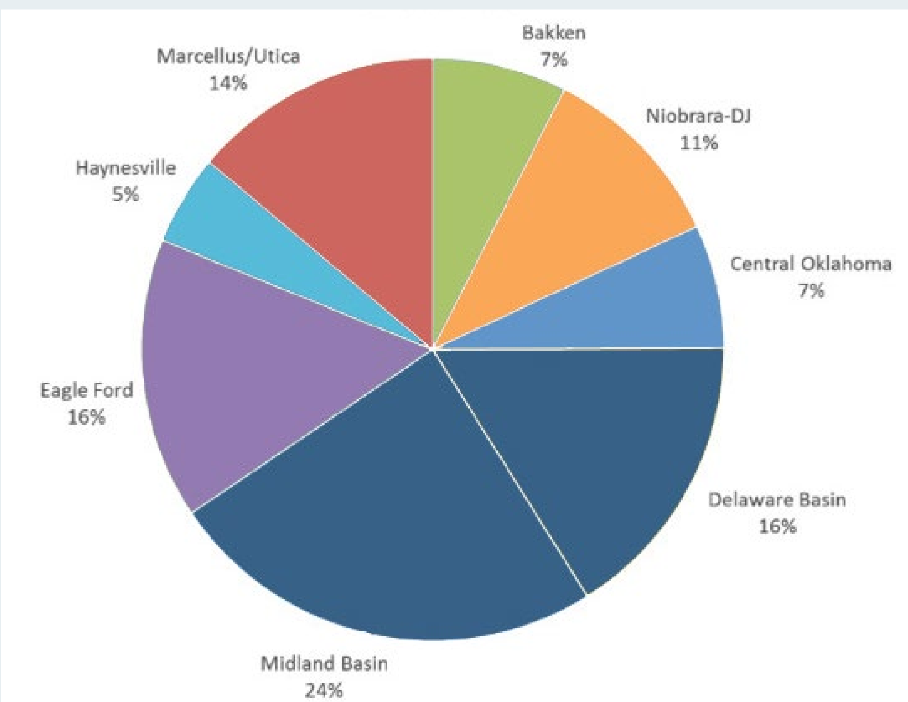

Figure 2-31: Water used in Hydraulic Fracturing for Top Basins/Regions in 2017

Source: After FracFocus® http://www.fracfocus.org

The Permian, Eagle Ford, and Appalachia regions accounted for 70 percent of the water used for hydraulic fracturing in 2017 across the key basins. The Permian (Delaware and Midland sub-basins) accounted for the greatest volumes, using 40 percent of the total across the key basins.

Water Disposal by County (Based on Available Data)

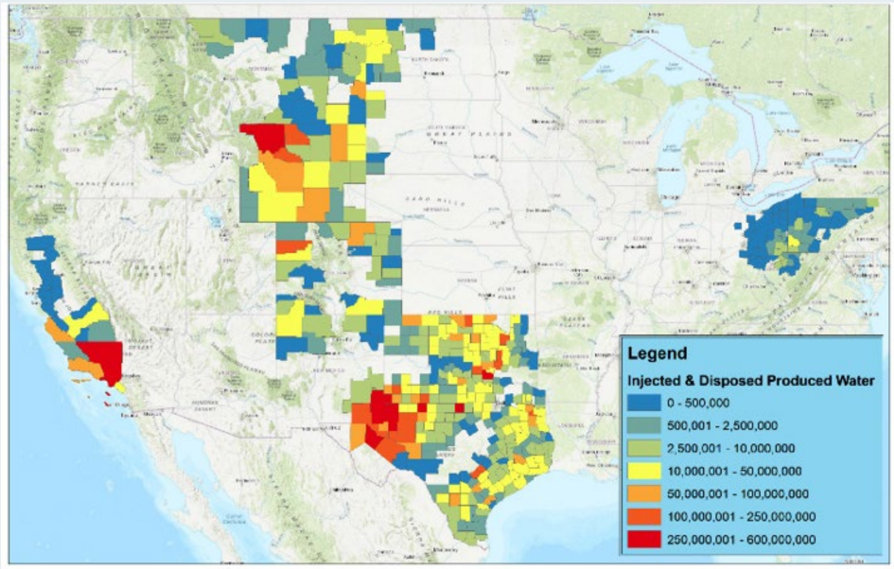

Figure 2-32: Injected Produced Water by County (bbl.) in 2017

Source: IHS Energy Group

Counties with high water disposal volumes—a proxy for high water production—are highlighted in red, orange, and yellow and are mostly concentrated in Texas and Oklahoma. This figure shows the estimated volume of injected produced water in barrels generated at a county level in 2017, where available. These volumes are a proxy for water production, but do not account for reuse or water crossing county lines.

Water Use for Hydraulic Fracturing per Well

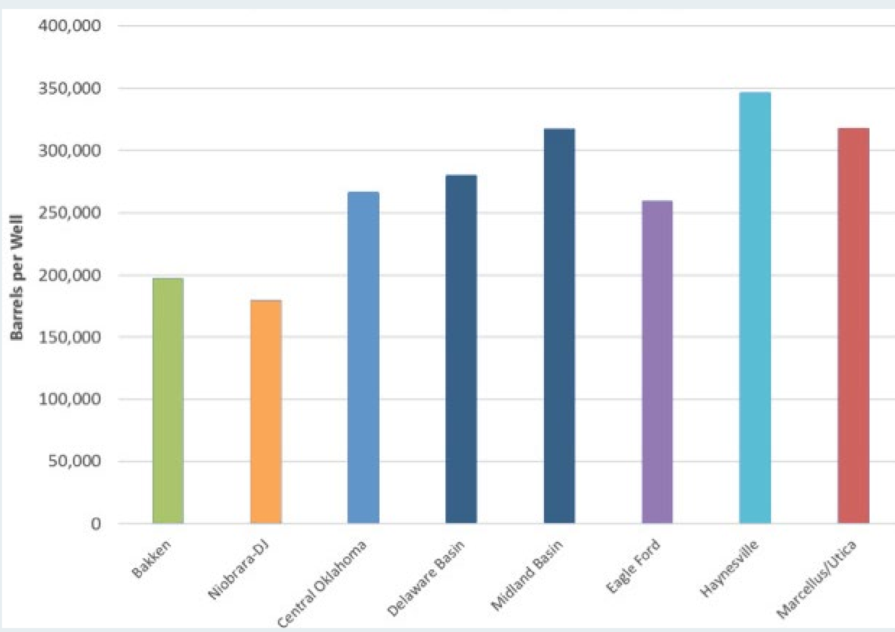

Figure 2-33: Water Use per Well in Hydraulic Fracturing for Key Basins/Regions in 2017

Source: After FracFocus®, http://www.fracfocus.org

The Haynesville and Marcellus natural gas-producing formations and the oil-producing Midland Basin used the highest water volumes per well in 2017. Per-well water use for hydraulic fracturing varies by formation properties and the length of the horizontal. Larger volumes of water needed and produced can provide the economics of scale to make reuse more viable. The multi-year trend has been for wells to use more water in their completion than previously required.

Typical Water Production by Well

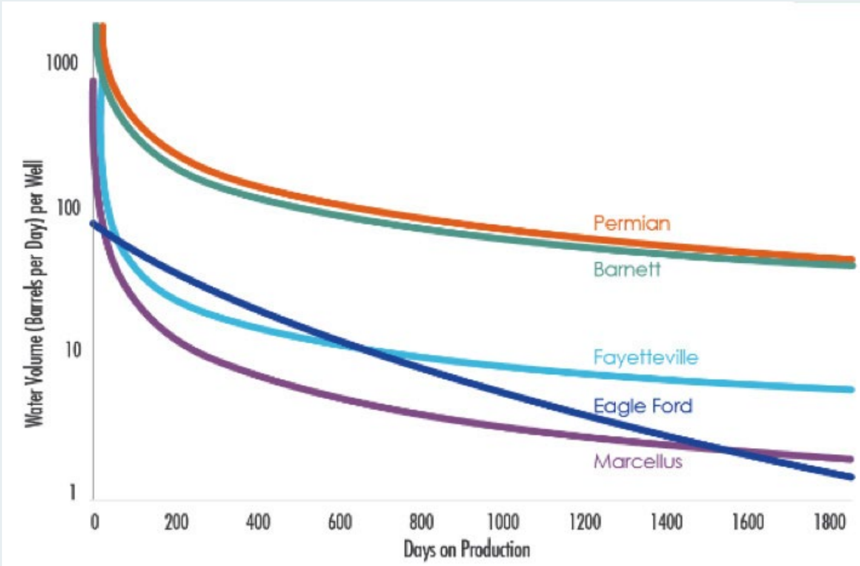

Figure 2-34: Typical Water Production by Well

Source: Energy Water Initiative 2015 Case Studies Report https://www.anadarko.com/content/documents/apc/Responsibility/EWI_Case_Studies_Report.pdf

While water production generally increases over time in conventional wells, it usually declines in unconventional wells in line with the well's oil and gas production. Declining water production can make single sourcing of reused water challenging or less viable.

Ratios of Produced Water to Sourced Water by Basin

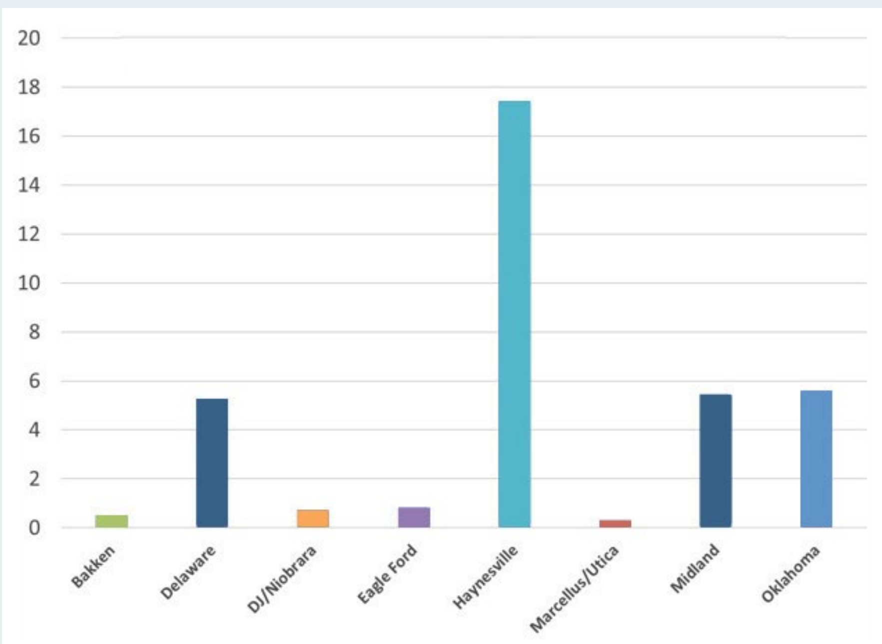

Figure 2-35: Produced Water to Sourced Water Ratio by Region for 2017

Source: After FracFocus®, http://www.fracfocus.org *and IHS Energy Group*

Haynesville, Permian, and Oklahoma have much more produced water than sourced water in 2017.* Produced water volumes in some regions far exceed the water volumes sourced for hydraulically fracturing of wells. Other regions, in contrast, produce less water than water sourced for hydraulic fracturing. The average amount of produced water over the life of a well varies from basin to basin and is influenced by the development maturity of an area, coupled with the number of wells drilled historically. The Haynesville area produced roughly 18 times as much water as was used in hydraulic fracturing in the area. Haynesville has conventional production that has substantial produced water and its water needs for hydraulic fracturing are relatively small. Comparing water volumes needed for hydraulic fracturing to the volume of produced water illuminates the potential balance of water for reuse.

* The produced water data is from IHS Energy Group, a company specializing in business information, and the sourced water data from FracFocus®. Counties with less than 100,000 barrels of sourced water in 2017 were excluded. Importantly, the produced water includes water from conventional production and enhanced oil recovery.

Ratios of Produced Water to Sourced Water by County

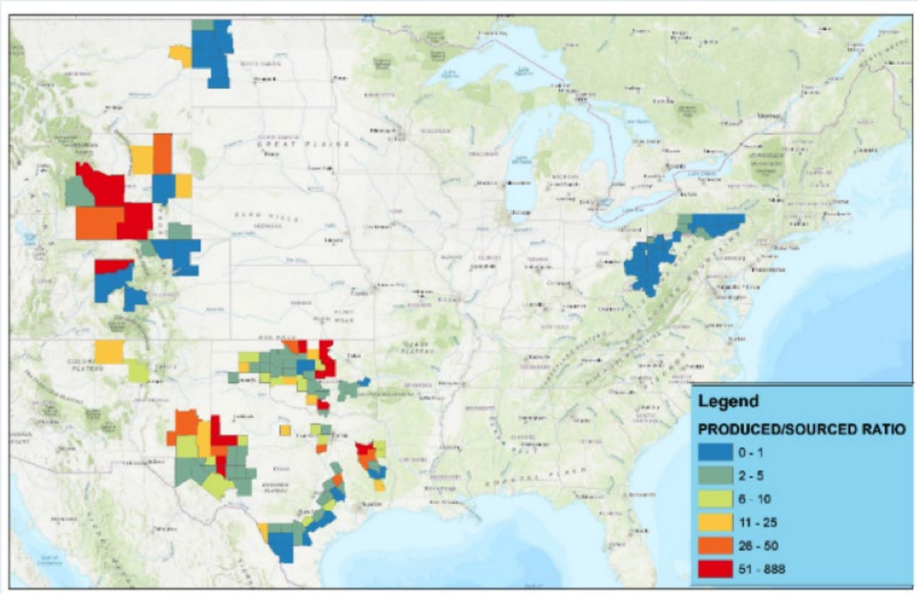

Figure 2-36: Ratio of Produced Water Divided by the Amount of Water Sourced for Completions by County for 2017

Sources: IHS Energy Group and FracFocus®

Water balance (supply divided by potential demand) varies significantly by county. Many areas in North Dakota, Ohio, Pennsylvania, West Virginia, and south Texas (counties shown in blue) are areas where produced water volumes were less than the sourced water needed. Based on the current production and completion activity, additional source water will always be needed in these areas even if all produced water is reused. In contrast, areas shown in red and orange have more produced water than the water needed for new completions.

Estimated Lifetime Ratios of Produced Water to Frac Volume by Basin

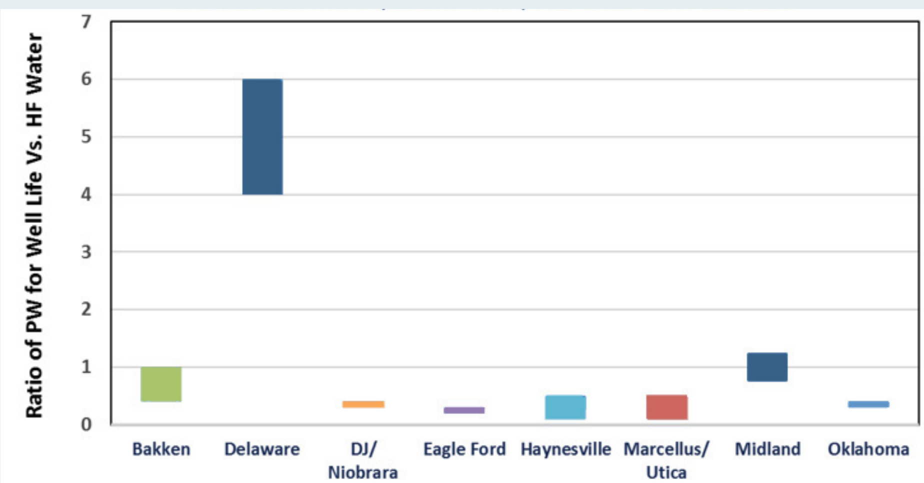

Figure 2-37: Ratio of Expected Lifetime Produced Water Divided by the Amount of Water Sourced for Completions

Source: Interviews with producers

In the long run of continuous drilling, the Delaware basin is expected to have far more produced water than can be reused in subsequent hydraulic fracturing. The Midland and Bakken areas are second and third in this ratio. These ratios are based on estimates provided by operators (typically five to ten operators per basin) when asked what amount of produced water will result over the life of the well compared to the amount used to hydraulically fracture the well. The ratio of four to six times produced water to fracture volume for the Delaware stands out among the basins.

Estimated Percentage of Produced Water Transported via Pipeline by Basin

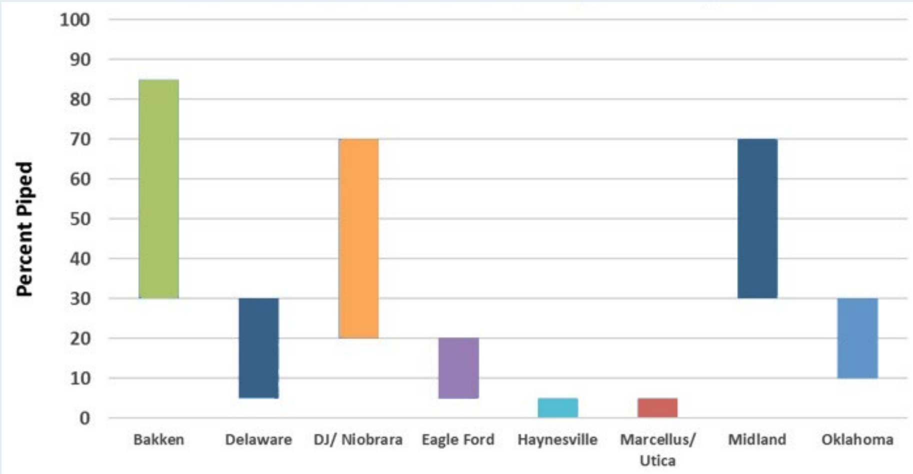

Figure 2-38: Percentage of Current Water Volumes Transported via Pipelines to Disposal

Source: Interviews with producers

Basins vary greatly in the amount of produced water transported to SWDs via pipelines. These estimated percentages are based on interviews with producers. Having interconnected salt water disposal pipelines facilitates the gathering of produced water and its potential reuse. The pipelines provide economies of scale for re-use and reduce trucking. Capacity of pipeline infrastructure is also dependent on when unconventional development of a particular field began. It takes time for buildout. Therefore, more is trucked in the first year or longer. The buildout of pipelines to move produced water to disposal wells is ongoing where it is economically feasible, usually when higher volumes of water justify the pipeline capital cost.

Permian Basin (Delaware and Midland Sub-Basins)

The Permian Basin in West Texas and the adjoining area of southeastern New Mexico underlies an area approximately 250 miles wide and 300 miles long.[65] The first commercial oil well in the Permian Basin was completed in 1921. As the largest petroleum-producing basin in the United States, the Permian has produced a cumulative 28.9 billion barrels of oil and 75 trillion cubic feet of gas to date. The Energy Information Administration (EIA) has estimated that the remaining reserves are 43 billion barrels of oil and 18 trillion cubic feet of gas. However, some experts claim the content is much larger, half a trillion barrels or even 2 trillion barrels. The switch to hydraulically fractured horizontal wells and unconventional formations began in 2011. Production in the Permian increased from about 1 million barrels per day in 2011 to about 3.3 million barrels per day in 2018 (Figure 2-24). Company spending increased, direct and indirect employment increased, and state and federal tax receipts increased.

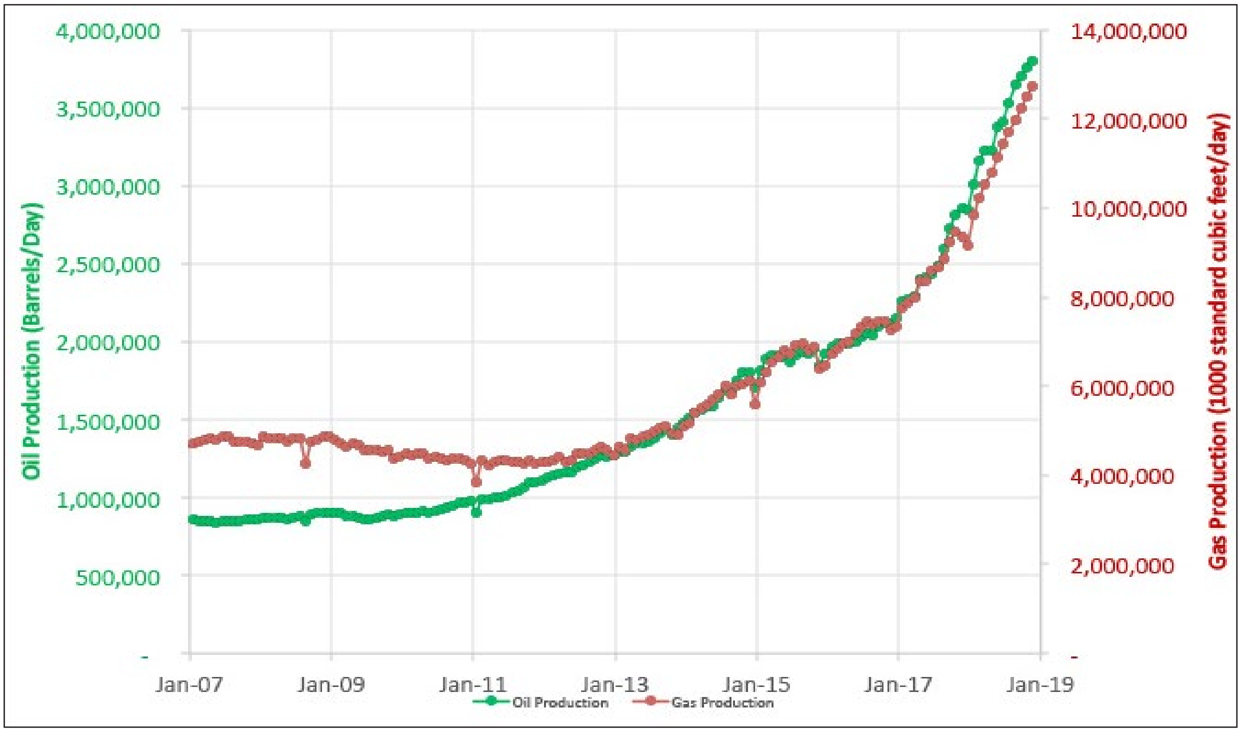

Figure 2-39: Permian Basin Oil and Gas Production
Source: EIA

As of December 2018, the Permian Basin had 485 active drilling rigs, which was 45 percent of the U.S. total and 23 percent of the worldwide rigs in operation.* Permian's oil production of 3.8 million barrels per day was over 45 percent of the U.S. oil production and more than 3.2 percent of world production. The Permian is the highest oil producing region in the United States and, if it were a country, would rank as the world's 10th highest producer.**

* Baker Hughes, North American Rig Count 2000-Current, http://phx.corporate-ir.net/phoenix.zhtml?c=79687&p=irol-reportsother

** EIA, International Energy Statistics, https://www.eia.gov/beta/international/rankings/#?prodact=53-1&cy=2017

The Permian Basin is the highest oil producing region in the United States and, if it were a country, would rank as the world's 10th highest producer.

65 Charles D. Vertrees, "Permian Basin," *Handbook of Texas Online*, (Texas State Historical Association: June 15, 2010), http://www.tshaonline.org/handbook/online/articles/ryp02.

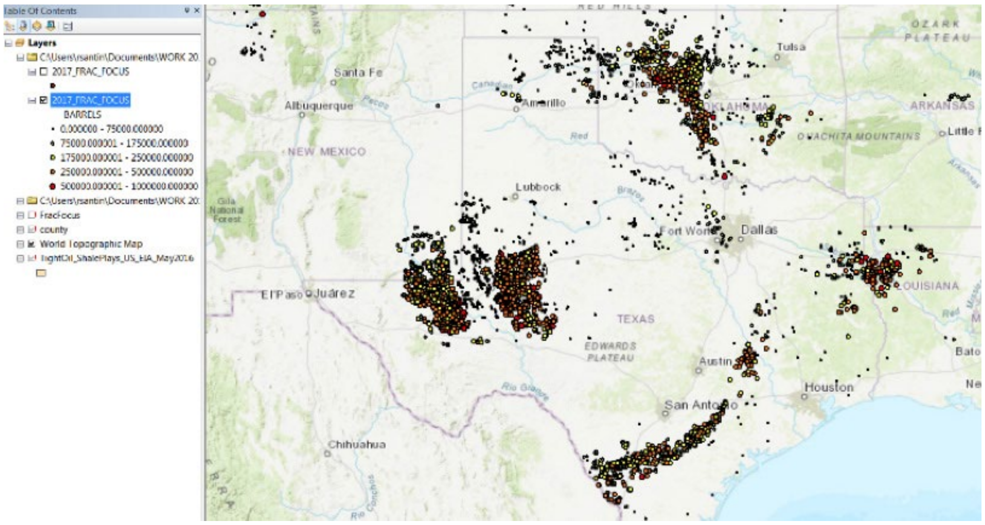

Figure 2-40: Water Source Plot for Individual Completion in Texas, Oklahoma, New Mexico, and Louisiana 2017

Source: After FracFocus® http://www.fracfocus.org

This map shows water sourced for individual completions in 2017 based on data from FracFocus®. Data includes the Permian in west Texas and southeast New Mexico, Oklahoma, the Haynesville in north Louisiana and east Texas, and the the Eagle Ford in south Texas.

The level of activity in west Texas and southeastern New Mexico strains water sourcing but offers opportunities for efficiencies in water management strategies. The demand for sourced water correlates to the rig count and the need for water disposal or reuse. New unconventional wells normally flow much higher water rates than older unconventional wells. Water sourcing is among several operational bottlenecks that have emerged in the Permian Basin. Such bottlenecks are normal for intense activity in an emerging market. Unconventional development often entails concentrated activity, which allows the building of water infrastructure and facilitates more produced water reuse than in areas with dispersed activity. All nine of the largest companies by market capitalization operating in Permian report reusing produced water in the region, representing a substantial increase in reuse compared to only a few years ago, when very few companies reported reusing water in the Permian. Historical information on the volume of reuse is not collected by any regulatory agency in Texas, nor are the reuse volumes typically reported elsewhere.

Many companies are building water networks to move the produced water by pipeline rather than by truck. This is a major investment toward reuse capability and results in reduced vehicle emissions and community disturbance. Based on industry news and company press releases, the Permian has more water projects (pipelines and reuse projects) ongoing than any other basin. The weighted average for water reuse in the Permian Basin was approximately 12 percent.

The Permian has more ongoing pipelines and reuse projects than any other basin. (Industry news and company press releases)

In the Delaware Basin, a sub-basin in the western part of the Permian Basin, an unusually high amount of water is produced over the life of a typical well. The produced water to completion volume is typically 400 to 600 percent. This large volume of produced water may put pressure on disposal capacity but may also provide a steady stream for reuse.

Discussions with Delaware Basin producers suggest that five to 30 percent of the produced water is transported by pipeline to salt water disposal wells or reuse treatment facilities. The water piped, as opposed to trucked, to disposal or reuse facilities is likely to grow over time.

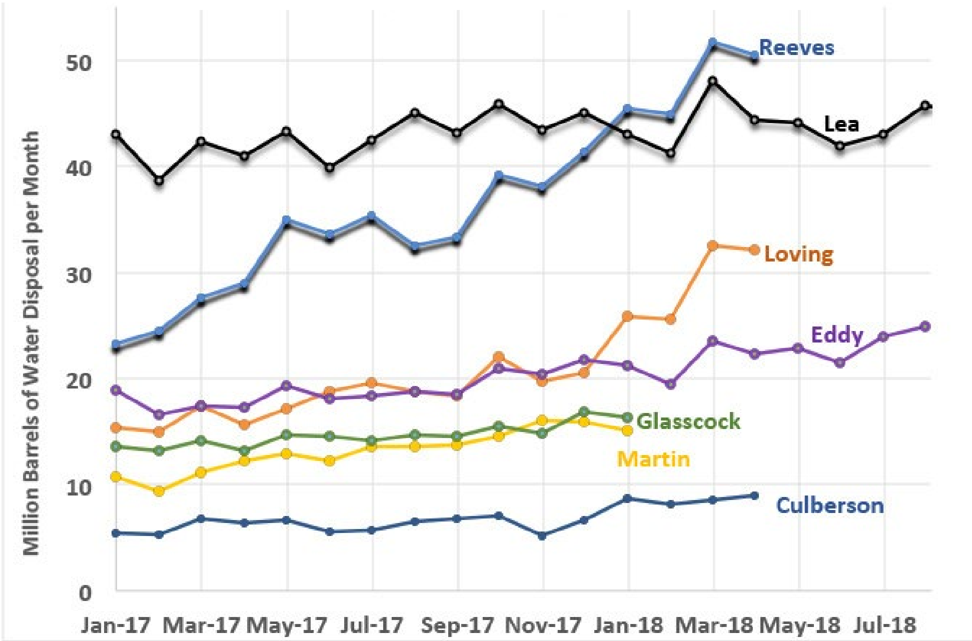

Figure 2-41: Produced Water Production for Selected Counties in Permian

Source: IHS

This figure plots monthly water disposal for some key counties in the Permian Basin. Both Reeves and Loving Counties had greater than 100 percent increases in water disposal from January 2017 to April 2018.

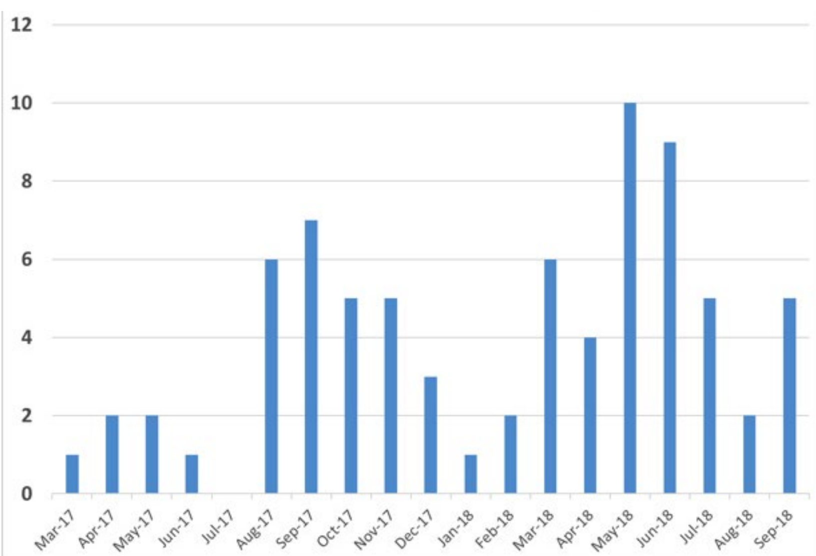

Figure 2-42: West Texas Seismicity Events per Month Above M 2.5

Source: BEG TexNet

West Texas has observed seismicity since at least the 1930s. Seismicity has recently increased in and near Reeves County, which is currently the most seismically active area in Texas. Unlike the plays in Oklahoma, the relationship between water disposal and seismicity remains more uncertain in west Texas. West Texas seismicity in the 1970s and 1980s was attributed to a mixture of natural pressure, inducement from production, and potential inducement from disposal/EOR. The geology is complex in west Texas and disposal is generally not into the deep formations close to basement rock, which can be more problematic. The TexNet seismic monitoring grid was initially installed in early 2017, and additional monitoring stations have been added. The addition of seismic monitoring stations result in a denser—and more sensitive—monitoring network, which may partially account for some of the increase in events. Research by both companies and universities is being done to better understand the seismicity issues. While seismicity is currently low in magnitude in a relatively sparsely populated area, it could be a concern if the trend continues and magnitudes of the quakes increase.

Drought is also a risk to communities and industry in the arid climate of Permian. In the drought year of 2011, Midland-Odessa, the unofficial capital of the Permian Basin, received only 5.5 inches of rain, instead of its normal 15-inch average. The drought put pressure on producing companies and spurred commitments to limit fresh water use. In 2013, Barnhart, Texas made national news when its one water supply well ran out of water and water had to be trucked in until a new well could be drilled.

The following are examples of water initiatives undertaken by oil and gas companies.

- **Shell** has taken steps to improve water recycling in one area of the Permian. Previously, groundwater used for hydraulic fracturing was transported through a 13-mile pipeline due to limited local water supply in this area. Since late 2016, the company replaced about 40 percent of this water by recycling produced water near a new development area. It now reuses produced water sourced from three saltwater disposal facilities.[66]
- In 2017, recycled produced water made up more than 40 percent of **Apache's** hydraulic fracturing water usage in some of its projects in the Midland Basin. The company's goal in 2018 is to raise that total closer to 50 percent where recycling is possible.[67]
- **Pioneer Natural Resources** is acquiring non-fresh water from three main sources: reuse of produced water after treatment, brackish groundwater sources, and treated industrial and municipal wastewater sources.[68]
- **SM Energy** is building a water pipeline infrastructure in Howard County, Texas, as shown in Figure 2-43. The company moves 95+ percent of the sourced water via pipelines. It will also connect produced water directly to disposal wells to reduce truck traffic.

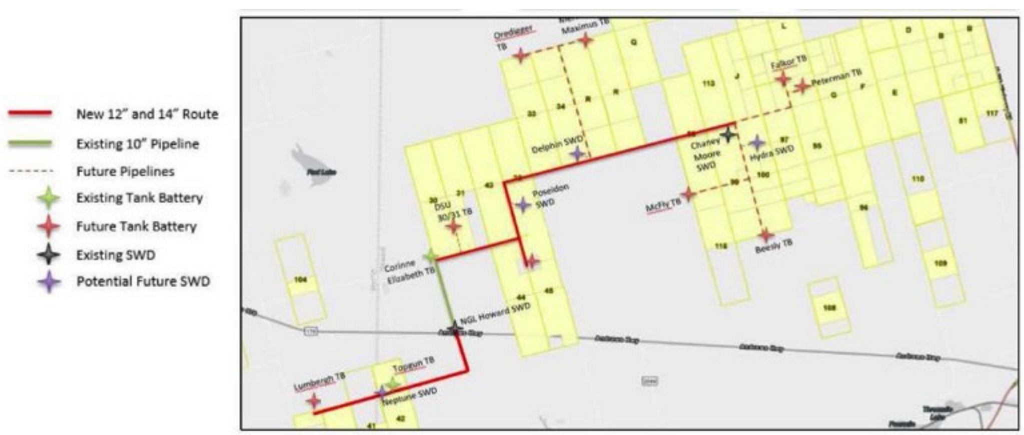

Figure 2-43: Water Pipeline in Howard County, Texas

Source: SM Energy https://s22.q4cdn.com/545644856/files/doc_presentations/2018/06/060118-June-Investor-Presentation.pdf

SM Energy is building a water pipeline infrastructure in Howard County, Texas, to move source water and transport produced water to disposal wells.

66 "Shell Sustainability Report 2017," Environment, Shell Global, http://reports.shell.com/sustainability-report/2017/our-performance-and-data/environment.html.

67 Stephen Whitfield, "Apache Aims to Boost Produced Water Reuse in Permian," *Oil Gas Facilities*, February 22, 2018, https://www.spe.org/en/ogf/ogf-article-detail/?art=3923.

68 "Water," Pioneer Natural Resources.

- **Fasken Oil and Ranch** is reusing produced water for hydraulic fracturing. Any water need not met by reuse is brackish water. Fasken had recycled over 5.5 million barrels of water as of 2016.[69]
- **Matador Resources** reported sourcing 26 percent of its 11.6 million barrels of water needed in 2017 from reused produced water in the Delaware Basin. As of May 2018, the company reported recycling more than 9 million barrels of water since its operations began in May 2015. Matador Resources operates water recycling facilities in the Delaware Basin, in Loving County, Texas, and in Eddy County, New Mexico. The facilities are capable of recycling about 160,000 barrels per day and will be expanded to 220,000 barrels per day. Prior to April 2017, 13 wells were stimulated with 100 percent recycled water. The company plans to expand its recycling efforts in other areas of the Permian Basin through 2018.[70,71]
- **Marathon Oil** took action to reduce waste and minimize freshwater use in the Permian Basin, including building a 300,000 barrel produced water storage and recycling facility within six months of their basin entry. The facility was treating and reusing produced water in stimulation jobs within three months of Marathon's acquisition and working to make produced water an economic supply source during droughts.
- More than 95 percent of the water used in **Chevron's** well completions in the Permian Basin is from brackish water sources.[72]
- **Solaris Midstream** has completed more than 50 miles of 12-inch and 16-inch produced water pipelines in Eddy and Lea Counties. It plans to build out 300 miles of high-capacity water lines through 2018.[73] In June 2018, Solaris acquired a private water supply company, adding more than 15 million barrels of industrial water per year, as well as access to significant sources of water, freshwater storage ponds, and more than 200 miles of water supply pipelines of varying sizes and associated rights-of-way.[74]

Permian case studies for Shell and XTO/ExxonMobil are described in Appendix 2-A.

Figure 2-44: Apache US-Permian Ketchum Mountain 403, United States: Permian Region

Photo courtesy of Apache, Inc.

Apache has set a goal of increasing recycling of its produced water in the Midland Basin.

69 *Year in Review 2016*, Railroad Commission of Texas, http://www.rrc.texas.gov/media/37377/2016-year-in-review.pdf.

70 Brian Walzel, "Permian Basin Operators Find Savings In Recycling Water," *Hart Energy E&P Newsletter*, April 7, 2017, https://www.epmag.com/permian-basin-operators-find-savings-recycling-water-1491921.

71 "Investor Presentation August 2018," Matador Resources Company.

72 "Water: responsible management of a critical natural resource," *Chevron Corporate Responsibility Report* (2017), https://www.chevron.com/corporate-responsibility/environment/water.

73 Luke Geiver, "Solaris completes phase one of major Delaware shale water system," *North American Shale Magazine*, May 29, 2018, http://www.northamericanshalemagazine.com/articles/2383/solaris-completes-phase-one-of-major-delaware-shale-water-system.

74 Casey Nikoloric, "Solaris Water Midstream Acquires New Mexico Water Supply Business from Vision Resource, Inc., and Launches Major Expansion on the Delaware Basin," *BusinessWire*, June 5, 2018, https://www.businesswire.com/news/home/20180605005883/en/Solaris-Water-Midstream-Acquires-New-Mexico-Water

Appalachia (Marcellus and Utica Formations)

The Appalachia basin extends across southwestern New York, northern and western Pennsylvania, eastern Ohio, and all of West Virginia. Appalachia was the heart of the global oil industry in the 1860s and 1870s. Almost as quickly as it began, the boom in Appalachia ended, as regions in California and Texas became the new centers of the domestic industry. Oil production in the Appalachian region peaked around 1900.[75] Over 100 years later, horizontal drilling combined with hydraulic fracturing of the Marcellus and Utica formations in Appalachia took off in 2010. The impact on natural gas production has been dramatic, increasing more than 20 times from early 2007 to December 2018 (Figure 2-45).

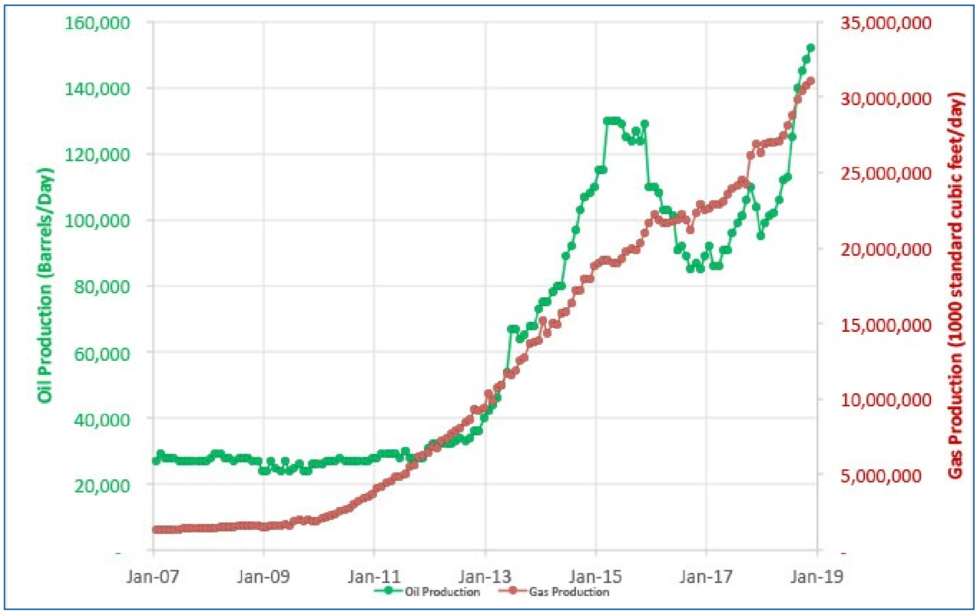

Figure 2-45: Appalachian Basin Oil and Natural Gas Production

Source: EIA

The Appalachian formations of the Marcellus and Utica produced approximately 31 billion cubic feet (BCF) of natural gas in December 2018. This made Appalachia the highest producing natural gas region in the United States.

75 *American Oil and Gas Families: Appalachian Basin Independents*, American Oil and Gas Historical Society (2004), https://aoghs.org/pdf/Publication-Appalachian-BasinIndependents.pdf.

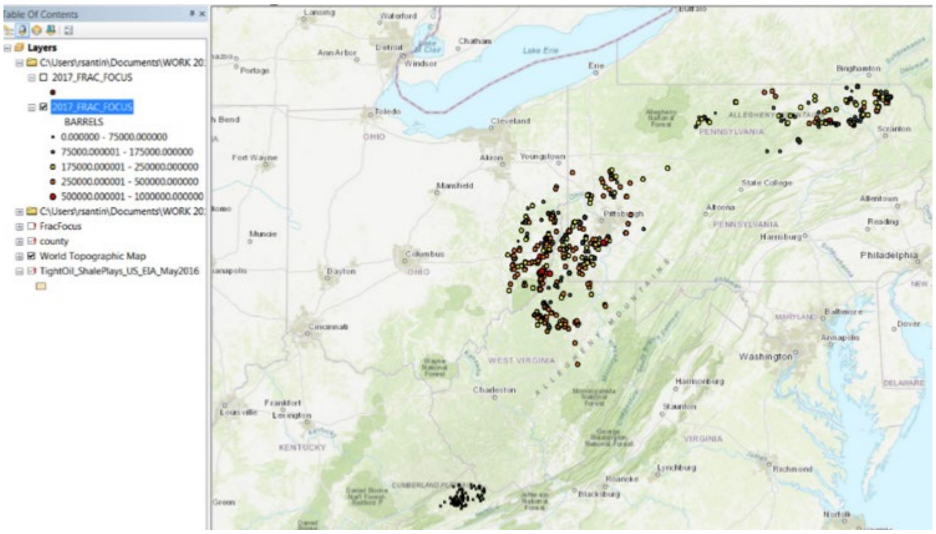

Figure 2-46: Water Source Plot for Individual Completion in Ohio, Pennsylvania, and West Virginia 2017

Source: After FracFocus®

This figure shows water sourced for individual completions in 2017 based on data from FracFocus®.

Figure 2-46 shows water sourced for individual completions in 2017 based on data from FracFocus®. Data includes the Marcellus and Utica activity in Ohio, Pennsylvania, and West Virgina. Surface water is often used as a supplement to reused produced water in these areas, due to the plentiful sources of surface water.

One factor affecting water management in the Appalachian Basin is the potential for induced seismicity associated with injection. In 2011, a series of earthquakes near Youngstown, Ohio, with magnitudes ranging from 2.1 to 4.0 were linked to a produced water disposal well nearby.[76] Concerns about seismicity in Ohio led to a temporary moratorium on new injection well permits following the seismic events at the Northstar well near Youngstown until emergency rules were enacted. Pennsylvania already had limited disposal wells based on factors such as minimal appropriate geology for disposal and the time required to obtain federal UIC permits.

Faced with limited disposal options and high disposal cost, Marcellus and Utica operators in Pennsylvania became early adoptors of produced water reuse. When the alternative is to truck water for significant distances for disposal, reuse offers lower cost when it can be coordinated operationally. The extremely limited disposal in Pennsylvania and, to a lesser extent, West Virginia, sets the Appalachian area apart from other major regions that typically had adequate disposal capacity predating hydraulic fracturing development.

As noted in a report by the American Geosciences Institute, "The Marcellus shale in the northern Appalachians produces very little water compared to other major oil- and gas-producing regions. Almost all of the produced water is reused in hydraulic fracturing operations, but the small amount of water produced compared to the amount used means that produced water can provide only a small fraction of the water needed for hydraulic fracturing in this area."[77] The small amount of water produced is normally highly diluted with additional fresh water to makeup the necessary volumes, thus reducing the need for treatment of the produced water for reuse in hydraulic fracturing.

According to the Pennsylvania Department of Environmental Protection, reuse of produced water was approximately 90 percent with the other 10 percent being disposed in disposal wells in 2013.

Ohio currently has 217 active injection wells that have been used by Ohio producers to successfully manage nearly all produced water in the area. Prior to the increase in water injection from shale development, approximately 6 million barrels of water were injected annually in Ohio. In 2017, 37.8 million barrels of water were injected with 48 percent coming from Pennsylvania, West Virginia, and New York.

76 GWPC and IOGCC, *Potential Injection-Induced Seismicity Associated with Oil & Gas Development: A Primer on Technical and Regulatory Considerations Informing Risk Management and Mitigation*, Second Edition (2017), http://www.gwpc.org/sites/default/files/ISWG%20Primer%20Second%20Edition%20Final%2011-17-2017.pdf.

77 Edith Allison and Ben Mandler, *Petroleum and the Environment*, The American Geosciences Institute (2018), ISBN: 978-1721175468, https://www.americangeosciences.org/sites/default/files/AGI_PetroleumEnvironment_web.pdf.

Company web sites report various reuse water initiatives in Appalachia.

- **Chevron** in the Appalachian region reused 97 percent of its produced water in 2014 and 2015. Chevron Appalachia has created water-sharing agreements with select local operators that facilitate reuse of Chevron's produced water by other operators for their drilling and hydraulic fracturing activities. This practice has multifaceted benefits, including maximizing water recycling to offset freshwater demands and limiting disposal to injection wells. Since the execution of agreements in March 2017, Chevron Appalachia has shared approximately 500,000 barrels of water.[78]
- **Antero Resources**, in partnership with the water treatment company **Veolia North America**, is developing a 60,000 barrel per day water treatment plant in Doddridge County, West Virginia for nearly $500 million. The complex, shown in Figure 2-47, allows Antero to treat and reuse flowback and produced water rather than permanently dispose of the water in injection wells.[79] Although the treated produced water is primarily intended to be reused in new wells, the desalination advanced treatment creates low TDS water and reduces the risk from any spills during water transfers.

Figure 2-47: Antero Water Treatment Plant in West Virginia
Photo courtesy of Antero Resources

Antero Resources developed this water treatment facility in partnership with Veolia North America.

- In **Range Resources Corp's** core operating area, the Marcellus Shale, "Range uses treated water from Pennsylvania-permitted treatment facilities that originated from other Exploration & Production (E&P) operators within the area. This contributes to a play-wide recycling and reuse program. Range recycles nearly 100 percent of its produced/process water from its E&P operations. This represents a significant percentage of our total water usage."[80]
- In 2017, **Southwestern Energy** started a water infrastructure project throughout its West Virginia Panhandle acreage in southwestern Appalachia. The pipeline system will source water from the Ohio River and distribute it to wellpads. The project will be built out in phases to provide fresh water for the company's wellpads and hydraulic fracturing operations. The system will have the potential to later be expanded to carry wastewater away from the wellpads for reuse.

78 "Water: responsible management of a critical natural resource," *Chevron Corporate Responsibility Report* (2017), https://www.chevron.com/corporate-responsibility/environment/water.

79 "Antero Clearwater Facility & Landfill," Water Management, Water, Sustainability, Community and Sustainability, Antero Resources, https://www.anteroresources.com/sustainability/water/water-management.

80 "When wastewater isn't wasted: Water reuse and recycling in America's public and private sectors," CDP North America, (formerly the Carbon Disclosure Project), (March 2017), https://6fefcbb86e61af1b2fc4-c70d8ead6ced550b4d987d7c03fcdd1d.ssl.cf3.rackcdn.com/cms/reports/documents/000/001/861/original/When_wastewater_isn't_wasted.pdf?1490176134

- **Southwest Energy** shares its produced water in West Virginia and Pennsylvania with other companies. Southwest's teams built relationships with the adjacent operators, worked out water-sharing agreements for both fresh and reuse water, and planned efficient transportation routes. As a result, in 2016 more than 708,000 barrels of produced water, which would otherwise have been disposed, was instead used by other operators for hydraulic fracturing.[81]

The Marcellus and Utica region has led other basins in the development of commercial water treatment plants. The commercial plants, some starting operations as early as 2010, will typically take water from multiple producers. The plants treat and may store the water until it is needed for reuse.

- **Eureka Resources** has three commercial water treatment plants in Pennsylvania. Although two of the plants have a permit to discharge treated water to the Susquehanna River, most of the water is reused for other oil and gas operations. The plants have a treatment capacity of 10,000 barrels per day. In addition to treating the water, one plant is also removing methanol from the water and reselling it for natural gas operations in the area. A different Eureka plant recovers sodium chloride (salt) and calcium chloride for industrial sales.

Figure 2-48: Eureka's Standing Stone Commercial Water Treatment Facility

Photo courtesy of Eureka

Standing Stone is one of three commercial water treatment facilities operated by Eureka Resources in Pennsylvania.

- **Fairmont Brine Processing** has a permit to discharge treated produced water from its commerical plant in Marion County, West Virgina. The plant has a capacity of 5,000 barrels per day. In addition to treating the water, the plant recovers and sells salt and calcium chloride. The company reports that treatment costs are about $4/barrel for the existing plant, but a second plant that is to be constructed at three times the size of their first plant would have treatment fees around $2.50/barrel, based on economies of scale.

Figure 2-49: Fairmont Brine Plant in Marion County, West Virginia

Photo courtesy of Fairmont

Fairmont Brine sells salt and calcium chloride produced in this West Virginia water processing plant.

81 *Corporate Responsibility Report 2016-2017*, Southwestern Energy®.

The EPA released a report in May 2018 that included a listing of facilities that have permits to discharge treated produced water. All but one of the facilities are in the Pennsylvania, West Virginia, and Ohio region of the Marcellus/Utica plays (see Table 2-3).[82] However, not all discharge permits are issued by USEPA. Some are issued by state agencies.

Other commercial water treatment facilities may treat produced water for reuse and may not have discharge permits. This includes Hydro Recovery's three plants in Pennsylvania, Fluid Recovery Services' three plants in Pennsylvania, and RES Water's two plants in Pennsylvania.

Table 2-3: Summary of In-Scope Discharging CWT Facilities Treating Oil and Gas Extraction Wastes

Source: USEPA

Facility Name	City	State	Discharge Type	Facility Notes
Byrd/Judsonia Water Reuse/ Recycle Facility	Judsonia	AR	Direct	Facility is permitted for discharge but operates almost exlusively as a recycle facility and discharges infrequently.
Clarion Altela Environmental Services (CAES)	Clarion	PA	Direct	Facility is permitted for discharge, but as of late 2016 facility was not accepting wastewater for discharge.
Eureka Resources, Standing Stone Facility	Wysox	PA	Direct	
Eureka Resources, Williamsport 2nd Street Plant	Williamsport	PA	Indirect	
Fairmont Brine Processing, LLC	Fairmont	WV	Direct	
Fluid Recovery Services: Frankling Facility (Aquatech)	Franklin	PA	Direct	Facility is not currently permitted under part 437, but revised permit expected to contain part 437 limitations.
Fluid Recovery Services: Creekside Facility (Aquatech)	Josephine	PA	Direct	Facility is not currently permitted under part 437, but revised permit expected to contain part 437 limitations.
Max Environmental Technologies, Inc – Yukon Facility	Yukon	PA	Direct	Accepts drilling muds and cuttings for stabilization and solidification along with other industrial wastes. Facility is permitted for discharge of CWT wastes.
Patriot Water Treatment, LLC	Warren	OH	Indirect	
Waste Treatment Corporation	Warren	PA	Direct	

Note: EPA identified one additional facility, the CARES McKean facility in Pennsylvania, that was previously permitted under Part 437. However, the most recent permit for this facility issued in 2016 no longer includes the CWT ELGs, indicating that this facility no longer discharges process wastewater from Part 437-regulated activities.

82 USEPA, *Detailed Study of the Centralized Waste Treatment Point Source Category for Facilities Managing Oil and Gas Extraction Wastes*, EPA-821-R-18-004 (May 2018), https://www.epa.gov/sites/production/files/2018-05/documents/cwt-study_may-2018.pdf.

Eagle Ford (South Texas)
South Texas oil and gas production dates back more than 100 years. Several formations were actively developed in the 1980s and 1990s. Production from the formation via hydraulically fractured horizontal wells increased dramatically starting about 2010. The Eagle Ford formation is the second highest producing oil basin and natural gas liquids region in the United States, producing approximately 1.4 million barrels per day in December 2018, according to the EIA (Figure 2-50).

Produced water reuse is economically challenging in Eagle Ford. Over its life, a typical Eagle Ford well may produce only 20 to 30 percent of the water used in completion (fracture treatment). These relatively small volumes of produced water are more costly to aggregate and distribute for reuse on a per barrel basis than the larger water volumes found in other regions. Additionally, the lower volumes of produced water have not driven up water disposal costs. Some companies are reusing limited volumes of produced water, but it is usually a special situation warranting the reuse. Many companies in Eagle Ford have sourced brackish water as a way to limit fresh water use. For example, Marathon Oil reports using 92 percent non-fresh water in 2017 in Eagle Ford, primarily brackish water.

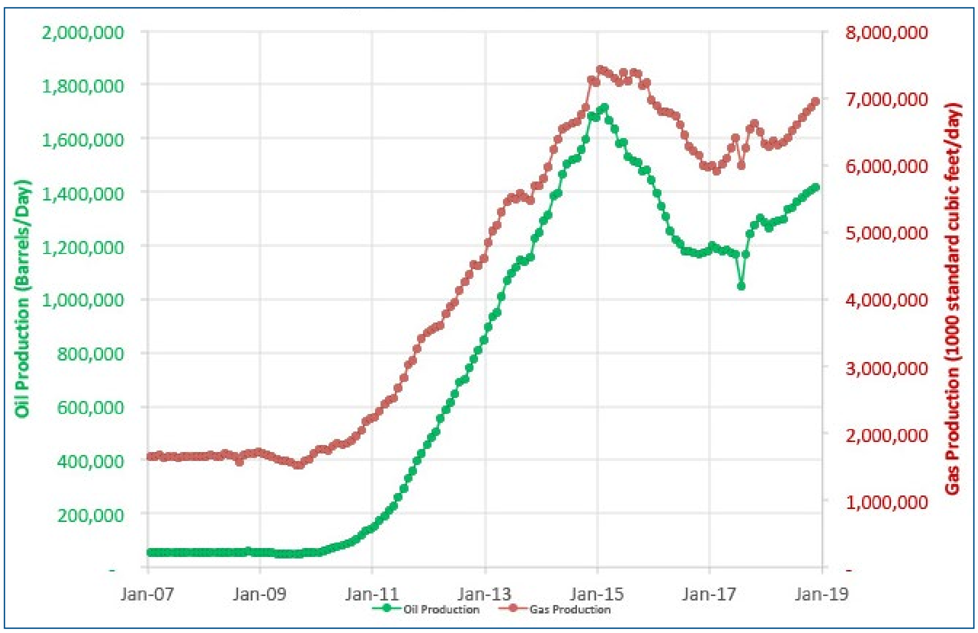

Figure 2-50: Eagle Ford Oil and Gas Production
Source: EIA

Oil and gas production in Eagle Ford have risen sharply since the start of unconventional operations.

Oklahoma

Oil was first discovered in Oklahoma, by accident, in 1859, near Salina, in a well that had been drilled for salt. In 1907, before Oklahoma became a state, it produced more oil than any other state or territory in the United States. From 1907 to 1930, Oklahoma and California traded the title of number one U.S. oil producer several times. Oklahoma oil production peaked in 1927, at 762,000 barrels per day.[83]

From January 2007 to December 2018, Oklahoma oil production increased by 355 percent and natural gas production increased by 88 percent based on data from the EIA as shown in Figure 2-51. The increase came from hydraulic fracturing of multiple formations in the central part of the state.

Oklahoma measured an increase in earthquakes over a magnitude 3 from 41 in 2010 to a peak of 903 in 2015. The number of events decreased to 304 in 2017. The Oklahoma Geological Survey has determined that the majority of recent earthquakes in central and north-central Oklahoma are very likely induced by the injection of produced water into deep disposal wells. A regulator and producer group has initiated projects to track and study the state's seismicity. The Oklahoma Corporation Commission (OCC), regulator of produced water injection wells, implemented approximately 11 mitigation plans between 2015 and 2017. Many of the actions involved restricting produced water disposal in areas adjacent to the seismic activity.[84] The reduction of magnitude 2.5 or greater earthquakes over the last two years in Oklahoma appears to demonstrate that problems with induced seismicity can be effectively managed with appropriate action (see Figure 2-52). In fact, a recent model by Stanford University predicts that the probability of a magnitude 5.0 or above is expected to fall from 32 percent in 2018 to 19 percent in 2020.[85]

Figure 2-51: Central Oklahoma Oil and Gas Production

Source: EIA

Increases in Oklahoma's oil and gas production have resulted from hydraulic fracturing of multiple formations in the central part of the state.

83 Crude Oil Production, Petroleum & Other Liquids, EIA (Release Date 2/28/2019) https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbblpd_m.htm.

84 "What We Know," Earthquakes in Oklahoma, Website of the Office of the Oklahoma Secretary of Energy and the Environment, https://earthquakes.ok.gov/what-we-know/.

85 Danielle Torrent Tucker, "Researchers pinpoint future probability of damaging human-made earthquakes," *Stanford News*, September 26, 2018, https://news.stanford.edu/2018/09/26/researchers-map-susceptibility-manmade-earthquakes/.

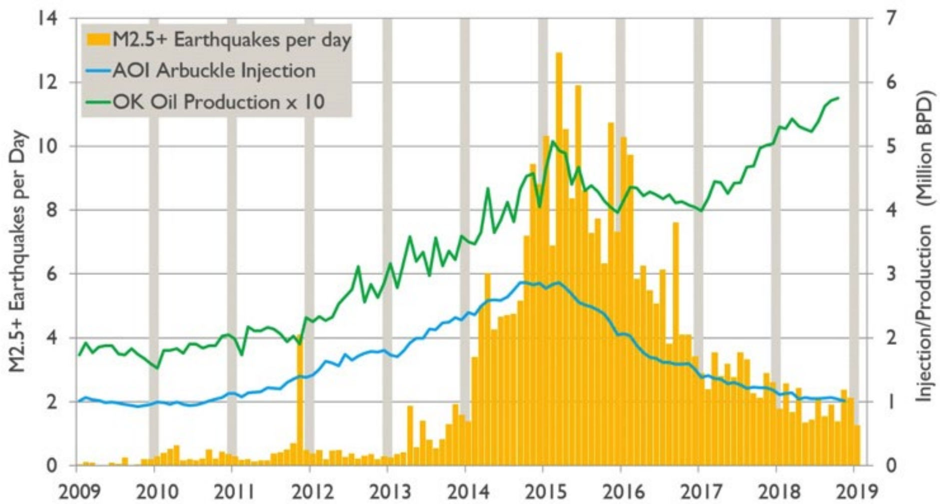

Figure 2-52: Oklahoma Earthquakes Greater than M 2.5

Source: Oklahoma Geological Survey

The reduction of magnitude > 2.5 earthquakes over the last two years in Oklahoma compared to the decrease in injection into the Arbuckle formation appears to indicate that problems with induced seismicity can be effectively managed with appropriate action.

The Ground Water Protection Council published a primer on seismicity in 2015 that has a summary of aspects of Oklahoma's seismicity. A second edition of the primer was published in 2017.[86]

In December 2015 Oklahoma Governor Mary Fallin established a fact-finding work group to look at ways that water produced in oil and natural gas operations may be recycled or reused instead of being injected into underground disposal wells. The Water for 2060 Produced Water Working Group has been charged with identifying regulatory, technical, and economic barriers to produced water reuse as well as looking at opportunities and challenges associated with treating produced water for beneficial uses, such as industrial use or crop irrigation. The April 2017 report on produced water in Oklahoma is available at https://www.owrb.ok.gov/2060/PWWG/pwwgfinalreport.pdf. The report included the following conclusions:

- Produced water reuse by the oil and gas industry is the most viable cost-effective alternative due to minimal water treatment needs and thus low treatment costs.
- The specific desalination cases evaluated for the study for reuse outside of oil and gas operations were significantly more costly than current operations or reuse for oil and gas operations.
- An evaluation case to transfer produced water from an area of excess to an area of need was somewhat encouraging.
- Enhanced evaporation was lower cost and more economically viable than the desalination cases.

The transfer pipeline and enhanced evaporation are the subjects of an ongoing study by the Oklahoma Water Resources Board.

Figure 2-40 shows water sourced for individual completions in 2017 in Oklahoma based on data from FracFocus®. Data includes Texas, Oklahoma, New Mexico, and Louisiana.

Oklahoma has a few specific water-related characteristics. For example, Oklahoma surface ownership is more fractionated than most other areas in the west. This makes obtaining right-of-way more difficult and magnifies landowner challenges. Additionally, central Oklahoma unconventional plays do not produce large amounts of produced water and the volumes quickly decline, reducing the economies of scale for reuse. Finally, brackish groundwater aquifers are undergoing research in some areas but are not extensively detailed in many locations; therefore, they are not widely utilized. Operators rely on surface and fresh groundwater sources.

86 GWPC and IOGCC, *Potential Injection-Induced Seismicity Associated with Oil & Gas Development: A Primer on Technical and Regulatory Considerations Informing Risk Management and Mitigation*, Second Edition (2017), http://www.gwpc.org/sites/default/files/ISWG%20Primer%20Second%20Edition%20Final%2011-17-2017.pdf.

In spite of the challenges unique to Oklahoma, several producing companies have taken action to reduce disposal by reusing produced water. For example:

- **Continental Resources** operates four recycling facilities in the SCOOP and STACK plays in central Oklahoma, which can recycle over 95,000 barrels of water per day (with a peaking capacity of 250,000 barrels per day) total at these facilities. Continental's ultimate goal is to reduce its fresh water use by approximately 50 percent within the service areas of its recycling facilities. Additionally, Continental works with the Oklahoma Corporation Commission and other producers to make available its recycling facilities when capacity is available, further reducing the industry's fresh water footprint.
- **Newfield** built a 30,000-barrels-per-day water treatment facility to facilitate reuse in Kingfisher County in 2017. From 2010 to 2017, Newfield constructed a 144-mile infrastructure system across its Oklahoma operating areas, with the majority of pipeline located in the SCOOP and STACK development areas. The pipeline infrastructure has reduced truck traffic on average by more than 60,000 round trips per year, taking more than 160 trucks off the road per day.[87] A more detailed case study of Newfield's Oklahoma operations is found in Appendix 2-A of this module.

Figure 2-53: Newfield's Storage and Reuse Facility in Kingfisher County, Oklahoma

In 2017, Newfield built this 30,000-barrels-per-day water treatment facility to facilitate water reuse in Kingfisher County.

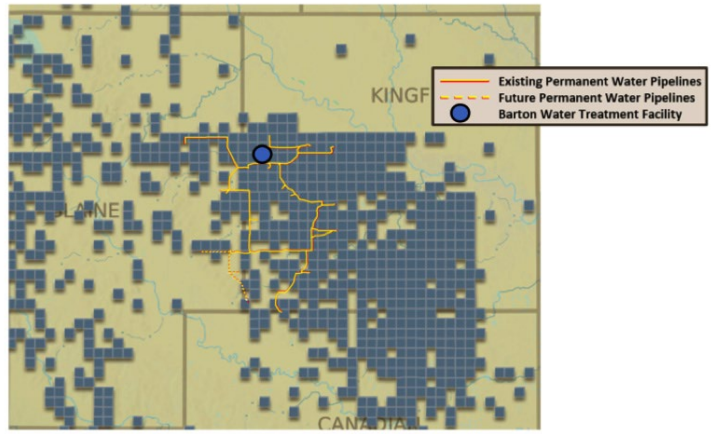

Figure 2-54: Newfield's Water Pipeline Network in Oklahoma

From 2010 to 2017, Newfield constructed a 144-mile water pipeline infrastructure system across its Oklahoma operating areas.

- In the STACK play in west-central Oklahoma, **Devon** built a pipeline network connecting well sites to a central water reuse facility. This conserved millions of barrels of water during a drought.[88]

87 *2017-2018 Corporate Responsibility Report*, Water Resource Management, Newfield Exploration Company.

88 "Understanding Water: Devon supports Oklahoma's 50-year water plan," Devon Energy Corporation, http://www.devonenergy.com/documents/sustainability/Water/Understanding-Water.pdf.

Niobrara/DJ Basin

The Niobrara Shale stretches through most of northern Colorado and eastern Wyoming, as well as into parts of Kansas and Nebraska. The two major oil and gas basins in the region are the Powder River Basin in northeast Wyoming and the Denver-Julesburg, or DJ Basin, in northeast Colorado and southwest Wyoming. The DJ Basin has the richest petroleum history of the two, dating to a 1901 oil discovery in Boulder County, Colorado. Today, the DJ Basin is known for the Wattenberg gas field, one of the largest natural gas deposits in the country. While the Powder River Basin is known more for coal production than for oil and gas, the application of horizontal drilling and hydraulic fracturing is driving oil production growth from that region's stacked shale plays (Figure 2-55).[89]

Figure 2-56 shows water sourced for individual completions in 2017 based on data from FracFocus®. Data includes the DJ Basin and Niobrara activity in Colorado and Wyoming.

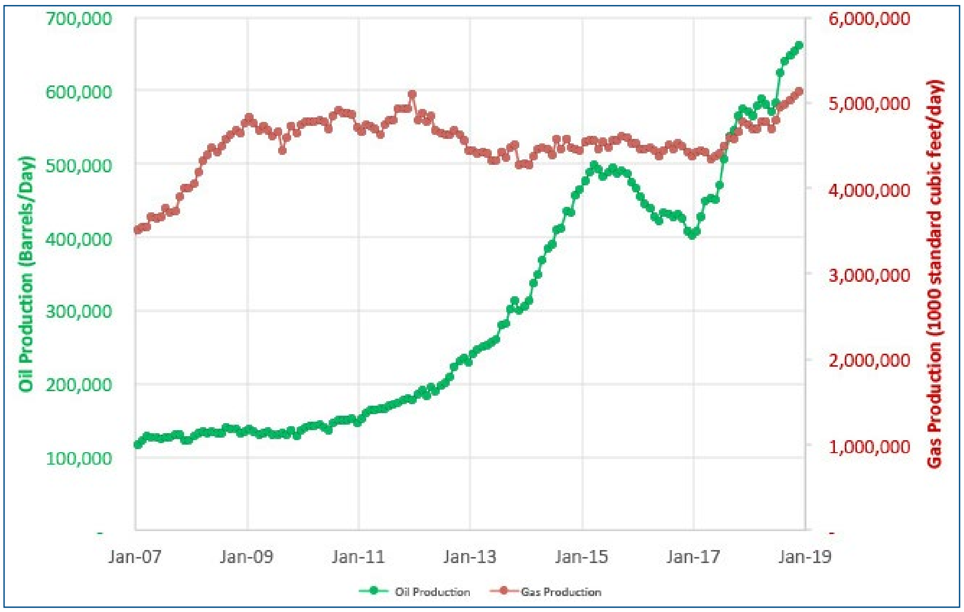

Figure 2-55: Niobrara/DJ Oil and Gas Production

Source: EIA

In the Powder River Basin, use of horizontal drilling and hydraulic fracturing is driving oil production growth from stacked shale plays.

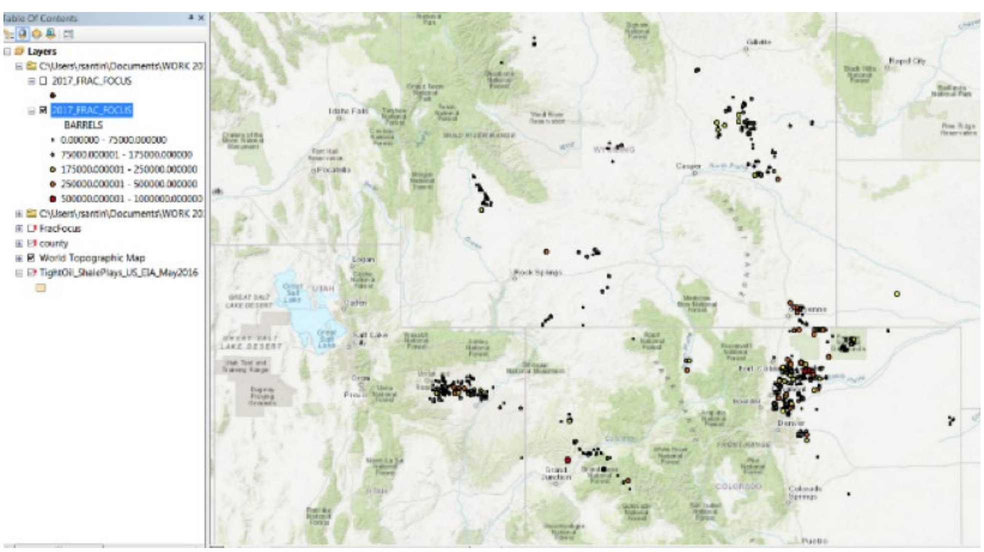

Figure 2-56: Water Source Plot for Individual Completion in Colorado and Wyoming in 2017

Source: FracFocus®

This figure shows water sourced for individual completions in 2017 based on data from FracFocus®.

89 Matthew DiLallo, "The 5 Companies Dominating the Niobrara Shale Play," *The Motley Fool*, August 25, 2016, https://www.fool.com/investing/2016/08/25/the-5-companies-dominating-the-niobrara-shale-play.aspx.

Following are examples of water management initiatives by producing companies in the Niobara/DJ Basin:

- **Anadarko Petroleum** has implemented water reuse programs and closed loop water management systems in the DJ basin. Its underground piping system eliminated approximately 8 million truck-miles in 2017.[90]
- In its Rockies plays, **EOG** has drilled water wells and installed water gathering and distribution infrastructure. This infrastructure allows water to be transported directly to EOG's well sites, decreasing EOG's need for trucking services. EOG has also invested in produced water gathering, recycling, and disposal infrastructure in the Rockies.[91]
- **Laramie Energy** has built a one-million-barrel lined treated water pond for produced water reuse in western Colorado. The system includes a significant amount of water lines and two pump stations for long distance delivery and reuse.[92]

A 5,000-well Powder River Basin project is being planned by five major companies in Wyoming. The BLM environmental study in January 2018 moved this project forward. It would be one of the largest single projects Wyoming has had go through the federal permitting process. However, a landowners advocacy group is concerned about the scale of drilling, including having enough sourced water and disposal capacity. The Converse county commissioner said water was also a local concern, but he believes the water issue can be solved.[93,94]

90 "Colorado Fact Sheet," Anadarko Petroleum Corporation (2017), https://www.anadarko.com/content/documents/apc/news/Fact_Sheets/Colorado_Fact_Sheet.pdf.

91 "Sustainability Report," EOG Resources (2017), https://www.eogresources.com/wp-content/uploads/2018/10/EOG_2017_Sustainability_Report_PROD.pdf.

92 Fifth Creek Energy, ENERCOM The Oil & Gas Conference, 2017.

93 "Powder River Basin Mega-Project: 5000-Well Project Edges Forward in Wyoming," Wold Energy Partners, January 30, 2018, http://www.woldenergypartners.com/news/2018/2/3/5000-well-prb-mega-project.

94 "Public, Government Agencies Divided Over 5,000-Well Oil & Gas Mega-Project in Wyoming," *Oil & Gas 360*, March 19, 2018, (from *Casper Star-Tribune*), https://www.oilandgas360.com/public-government-agencies-divided-over-5000-well-oil-gas-mega-project-in-wyoming/.

Bakken

Oil was first discovered within the Bakken in North Dakota in 1951, but past production efforts faced technical difficulties. The application of hydraulic fracturing and horizontal drilling technologies has caused a boom in Bakken oil production since 2000. The Bakken was first major commercial shale oil play in the U.S. and its production using hydraulic fracturing of horizontal wells broke new ground. In January 2011, Bakken oil production was already about 354,000 barrels per day, while Eagle Ford production was only 142,000 during the same period. In early 2011, very few hydraulically fractured horizontal wells had been completed in the Permian, cementing Bakken's claim to be the first unconventional oil play. Bakken production peaked in late 2014 before dipping in 2015 and 2016 during a period of extremely low crude oil prices. Figure 2-57 shows that current production in the Bakken is at an historic high.

Figure 2-58 shows water sourced for individual completions in 2017 based on data from FracFocus®. Data includes the Bakken formation of the Williston Basin activity in North Dakota.

A report by the American Geosciences Institute observed that "In the Bakken area of North Dakota only about 5 percent of the wells drilled in 2014 used produced water in their fracturing fluid. This is partly

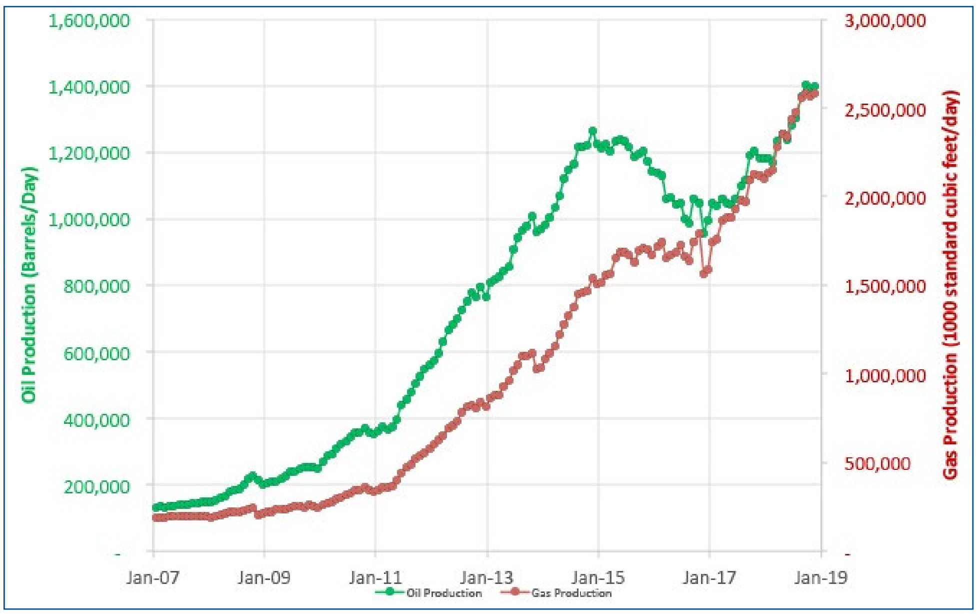

Figure 2-57: Bakken Oil and Gas Production

Source: EIA

Bakken was the first major commercial shale oil play. Current production in the formation is at an historic high.

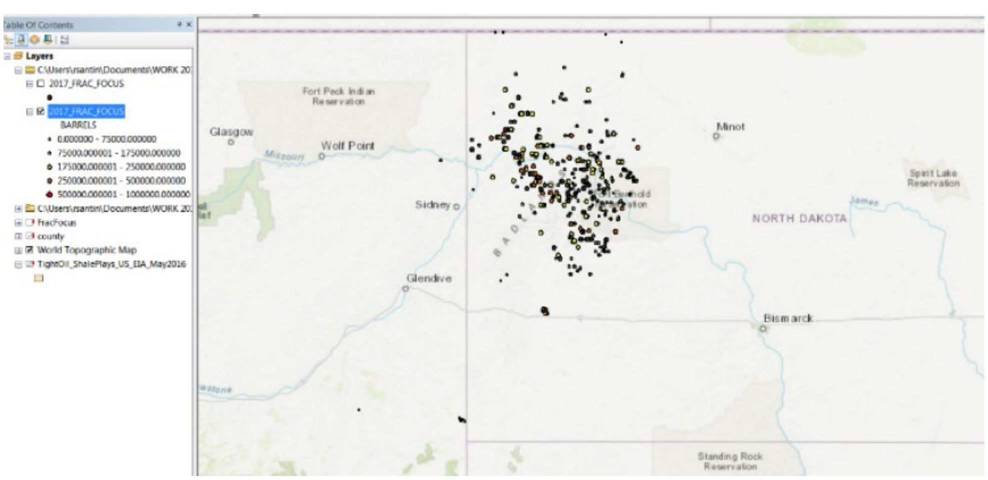

Figure 2-58: Water Source Plot for Individual Completion in the Bakken Area of North Dakota in 2017

Source: After FracFocus®

This figure shows the locations of water sourced in the Bakken region.

due to state regulations that prohibit storage of salty produced water in open-air pits and partly because the extreme salinity of produced water in this area makes treatment and reuse difficult and expensive."[95]

Examples of water management projects by producing companies in the Bakken include the following:

- **EOG** has a water reuse facility in the Bakken that began operating in 2012. The company also built a water pipeline system, consisting of more than 40 miles of dual 8-inch and 12-inch pipelines that carry water used in the completion process directly to the wellpads. This system reduces EOG's well completion costs and decreases water transportation by truck in Bakken-area communities.[96]
- **Hess** is using produced water in place of fresh water for production maintenance, which includes well workovers and well maintenance. In 2017, Hess reused approximately 2,000,000 barrels of produced water for this purpose instead of using fresh water.
- **Goodnight Midstream** operates 22 saltwater disposal wells (SWDs), including water pipeline infrastructure, in the Bakken. Where the pipe system connects to operator tank batteries, it eliminates the need to truck water to SWD wells. The interconnected produced water system could potentially be used for reuse if it becomes technically and economically feasible. A future increase in either sourced water costs or disposal costs could tip the balance and make reuse viable using this pipeline system.

Figure 2-59: ConocoPhillips Well in Bakken
Photo courtesy of ConocoPhillips

Oil was first discovered within the Bakken in North Dakota in 1951.

95 Edith Allison and Ben Mandler, *Petroleum and the Environment*, The American Geosciences Institute (2018), ISBN: 978-1721175468, https://www.americangeosciences.org/sites/default/files/AGI_PetroleumEnvironment_web.pdf.

96 "Sustainability Report," EOG Resources (2017), https://www.eogresources.com/wp-content/uploads/2018/10/EOG_2017_Sustainability_Report_PROD.pdf.

Haynesville

Geologists had long known that the Haynesville Formation in northern Louisana and eastern Texas contained vast quantities of natural gas. However, because of its low permeability, the Haynesville was originally considered only a source rock rather than a gas reservoir. In 2008, the successful application of horizontal drilling and hydraulic fracturing forever changed the Haynesville (Figure 2-60). The Haynesville Shale is now considered the second largest natural gas field in the United States, trailing only the Marcellus Shale. At its peak in 2010, nearly 190 drilling rigs were operating in the play. However, the success of this and other natural gas shale plays around the country pushed natural gas prices down to a level that substantially reduced rig count in the region until 2017.[97] However, even at a reduced rig count overall, production has risen to an all-time high due to more productive wells.

Figure 2-40 shows water sourced for individual completions in 2017 in the Haynesville based on data from FracFocus®. Data includes Texas, Oklahoma, New Mexico, and Louisiana.

The Sabine River and the region's many lakes provide surface water for sourcing in the Haynesville Play. However, the US Corps of Engineers and the rules of the states of Texas and Louisiana all come into play in this region. Companies are working with the river authorities on multi-year take-or-pay contracts. Typical costs for fresh water may range from \$0.05 to \$0.30 per barrel. Trucking costs may range from \$0.75 to \$1.50 per barrel.

Third party disposal costs average about \$1 per barrel. Occasionally, operators will share a water source with another producer. Some of the producers are concerned about disposal wells beginning to increase disposal formation pressure, although there has not been significant seismicity in the area.

The companies interviewed were not reusing produced water, but were aware of one producer that was reusing produced water. Because the Haynesville is still in the early delineation phase where wells are drilled in a more scattered fashion, the aggregation of water is difficult. An estimated 98 percent of water is trucked to SWDs. There is one small commercial reuse facility in northern Louisiana.

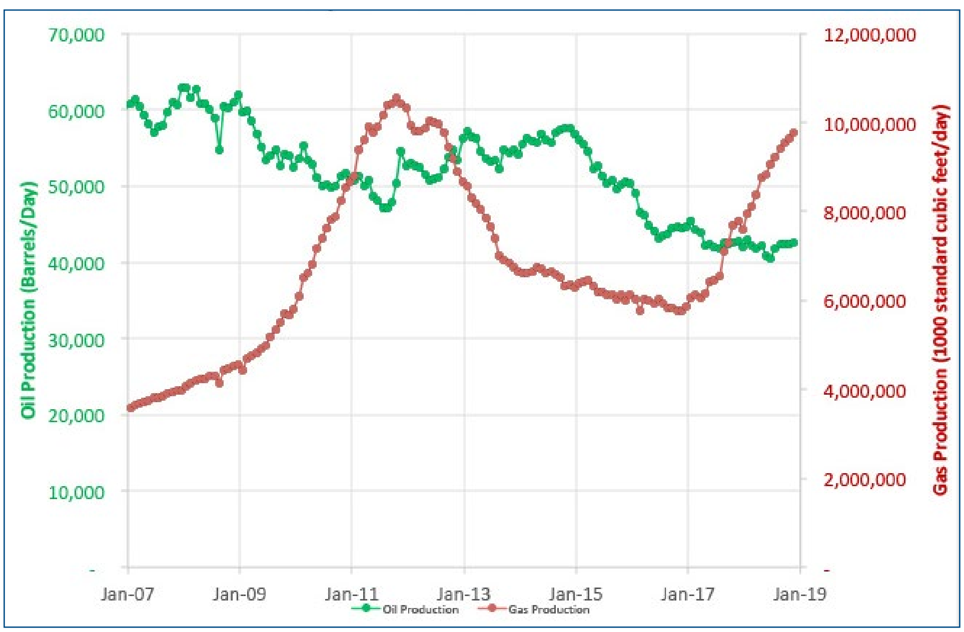

Figure 2-60: Haynesville Oil and Gas Production

Source: EIA

The Haynesville Shale is now considered the second largest natural gas field in the United States, trailing only the Marcellus Shale.

97 *"History of the Haynesville Shale,"* Universal Royalty Company (2013), http://www.universalroyaltyco.com/resources/history-haynesville-shale/.

PRODUCED WATER QUALITY DATA COMPILED FROM PRODUCING COMPANIES

Water quality data from 18 producing companies was gathered for this report. The American Petroleum Institute (API) helped with the gathering and compiling of the data. The companies reported the high and average values by basin for seven parameters. An average of the individual company's high numbers and average numbers are plotted in Figure 2-61 and Figure 2-62. The figures indicate that the produced water quality varies by a factor of four among the basins for a variety of components. The age of a well also influences its water quality; an individual well usually has an increasing TDS in the first weeks and months of production. Table 2-4 shows the data used in Figures 2-61 and 2-62.

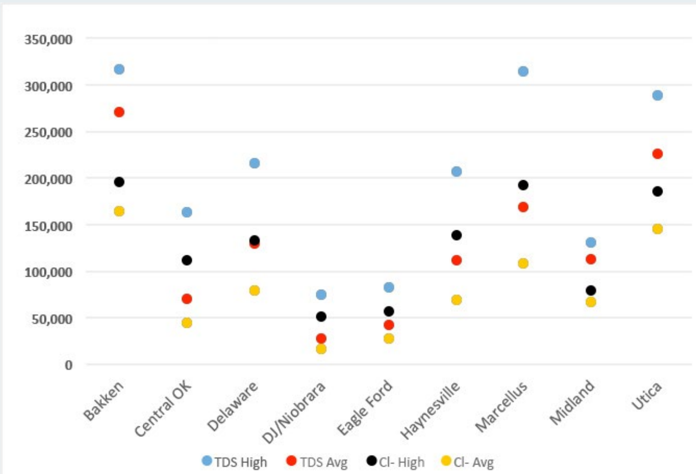

Figure 2-61: Water Quality Variation by Basin (TDS and Chlorides)

Source: 18 Producing Companies

Figures on Y axis represent Mg/L. Many basins have average TDS content ranging up to several times that of seawater.

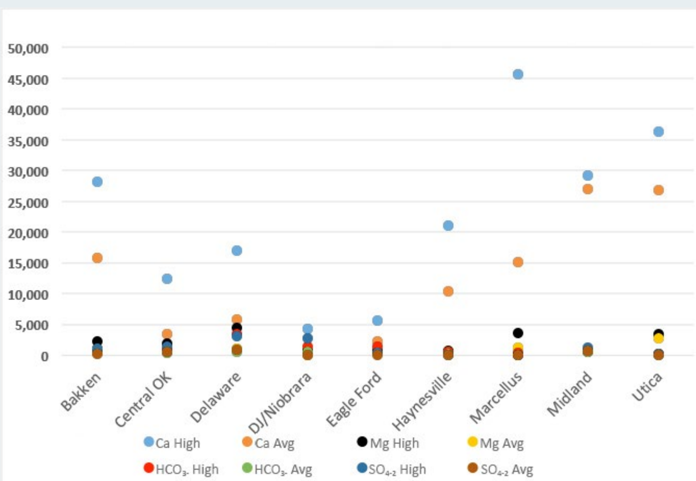

Figure 2-62: Water Quality Variation by Basin (Calcium, Magnesium, Bicarbonates, Sulfates)

Source: 18 Producing Companies

Table 2-4: Summary of Water Analysis Data from Producing Areas

Source: 18 producing companies

	pH		TDS (mg/l)		Calcium (mg/l)		Magnesium (mg/l)		Bicarbonates (mg/l)		Sulfates (mg/l)		Chlorides (mg/l)	
	High	Average	High	Average	High	Average	High	Average	High	Average	High	Average	High	Average
Bakken	7.2	5.9	317,040	270,743	28,184	15,886	2,198	1,164	530	451	1,109	271	195,999	164,756
Central OK	7.4	6.6	162,884	70,547	12,431	3,376	1,955	776	1,076	476	1,502	530	112,348	44,839
Delaware	7.7	6.7	216,319	129,354	17,078	5,892	4,410	1,150	3,410	516	3,060	904	132,995	79,719
DJ/Niobrara	8.3	7.0	74,940	28,238	4,298	574	766	64	1,382	561	2,849	80	51,289	16,470
Eagle Ford	7.6	6.5	82,669	41,999	5,607	2,300	769	341	1,348	378	399	94	56,850	27,893
Haynesville	7.1	5.5	206,835	111,551	21,121	10,470	812	502	590	199	127	13	138,583	68,965
Marcellus	7.2	6.0	315,118	169,177	45,724	15,207	3,626	1,326	345	137	55	11	192,694	108,748
Midland	7.4	6.7	130,841	112,885	29,139	27,059	659	496	753	489	1,292	754	79,293	66,606
Utica	6.5	5.9	288,318	226,590	36,374	26,874	3,398	2,715	230	67	222	23	185,583	145,253

PRODUCED WATER QUALITY BASED ON USGS DATA

The EPA characterized produced water in a recent study using the USGS produced water database. Figure 2-63 indicates some of the constituents and variation in TDS. Data for select parameters from the USGS database Version 2.2 are the minimum (excluding non-detect values), 25th percentile, median, 75th percentile, and maximum values for each parameter. For each constituent, the total number of samples and the number of samples with values greater than the detection limit are shown in parentheses (for example, there were 18,387 samples containing barium, 11,369 of which were greater than the detection limit). As illustrated in Figure 5-1, the concentration of these select parameters varies greatly across the country. An example is TDS, which can vary significantly by basin. Figure 5-2 shows the box and whisker plots with TDS concentration data for the 10 basins with the greatest number of samples contained in Version 2.2 of the USGS database (TDS values below 10 mg/L are not shown in this plot). As illustrated by these data, TDS concentrations for samples contained in the database vary greatly, both within a specific basin and across different basins.*

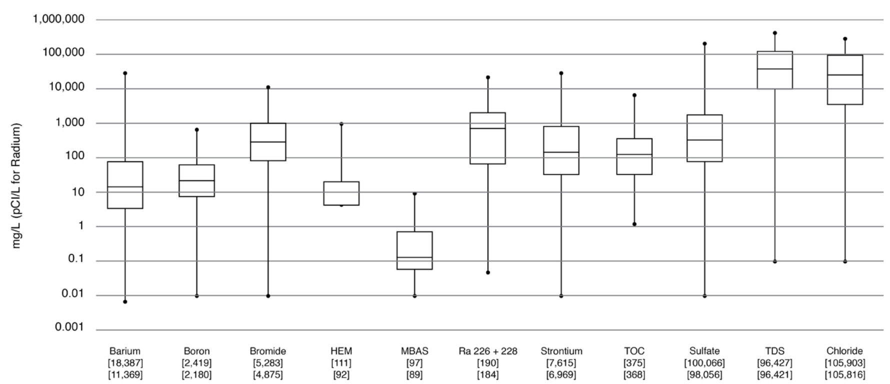

Figure 5-1. Oil and Gas Produced Water Constituent Concentration Data (USGS National Produced Waters Geochemical Database, V2.2)

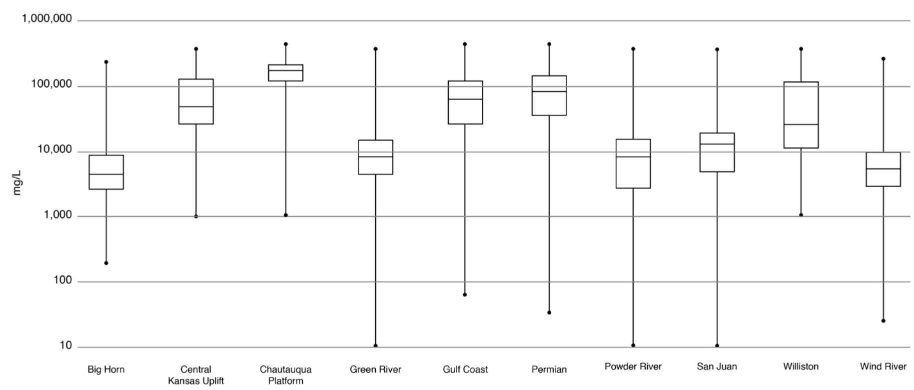

Figure 5-2. Oil and Gas Produced Water TDS Concentration by Basin (USGS National Produced Waters Geochemical Database, V2.2)

Figure 2-63: Figures 5-1 and 5-2: Oil and Natural Gas Produced Water TDS Concentration by Basin

Source: USGS National Produced Waters Geochemical Database, V2.2

* USEPA, *Detailed Study of the Centralized Waste Treatment Point Source Category for Facilities Managing Oil and Gas Extraction Wastes*, EPA-821-R-18-004, May 2018, 262 pp., https://www.epa.gov/sites/production/files/2018-05/documents/cwt-study_may-2018.pdf

MODULE 3

Produced Water Reuse and Research Needs Outside Oil and Gas Operations

MODULE SUMMARY

The objective of Module 3 is to promote an informed dialogue on current and future reuse of produced water outside oil and gas operations.
It examines the drivers for reuse and aims to define the information necessary for knowledgeable decision making by regulators, industry, and other stakeholders. It also provides insight on how to fill identified research needs.

Reuse of produced water outside oil and gas operations could take various forms.
Potential options for the treatment and reuse of produced water outside the oil and gas industry can be sorted into three primary categories: land application (e.g., irrigation, roadspreading), introduction to water bodies (e.g., discharges to surface water, injection or infiltration to ground water) and other industrial uses (e.g., industrial feed streams, product or mineral mining). Some options, such as surface water discharge, are active in limited circumstances today. Others, such as utilizing treated produced water in other industrial systems, are under investigation or theoretical.

Drivers for considering produced water reuse differ for industry and other stakeholders.
States and regulators may be driven to investigate reuse for reasons ranging from drought and groundwater depletion to disposal-related induced seismicity. For the oil and gas industry, operational and economic considerations, such as a reduction in nearby cost-effective disposal capacity, may drive a search for produced water management alternatives including reuse.

For the majority of anticipated reuse scenarios, produced water will be treated before reuse, using a "fit-for-purpose" approach.
Produced water quantity and quality is not uniform, and neither are the circumstances of its potential treatment and reuse. Under a "fit-for-purpose" mindset, research, treatment decisions, risk management strategies, and in some cases even approval processes should be tailored to address a particular produced water for a particular type of reuse. Not all reuse scenarios will require the same analysis or approach.

Treatment can take many forms, and the particular treatment utilized will depend on the desired quality needed to support the intended end use. Designing an appropriate treatment train will play a vital role in reducing potential risks to health and the environment. Treatment of produced water for reuse objectives that demand consistent high quality can present unique challenges such as managing variability; significantly reducing high total dissolved solid levels, difficult-to-treat organic constituents, and naturally occurring radioactive material; and handling residuals.

Potential risks to health and the environment must be well understood and appropriately managed in order to prevent unintended consequences of produced water reuse. Research objectives will also be "fit for purpose."
The traditional mechanisms for produced water management and disposal (namely underground injection) have not

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previously demanded a substantive understanding of the character of produced water or the risks of its intentional treatment and reuse or release. As reuse opportunities are assessed and decisions are made, advancing knowledge and understanding of produced water and potential risks to health and the environment from its reuse outside oil and gas operations is necessary to inform the development of protective programs. These research and data collection efforts should be "fit for purpose" similar to treatment technologies, as the questions and information necessary will be specific to the particular produced water and reuse scenario envisioned.

Beyond managing health and environmental risks, other challenges must be weighed in determining the feasibility of a produced water reuse program.
Costs and risks related to potential reuse programs include legal and regulatory questions concerning authorization or permitting for reuse; understanding and managing public perception of the reuse program; logistical considerations relating to timing and necessary infrastructure; costs of treatment, transportation, and solids management; the potential need to adapt contractual commitments; fluctuations in energy supply and demand; market-related costs or opportunities; and water rights issues. Environmental considerations beyond direct health or ecosystem impacts include emissions from treatment, managing waste materials from treatment, cumulative ecosystem impacts, or other localized issues. Identifying benefits of reuse proposals—such as a greater ability to meet the needs of downstream water users or a reduction in disposal-related seismicity—allows trade-offs for different reuse opportunities to be considered.

Data and information currently available may not be adequate to support reuse programs that protect human health and the environment with an acceptable level of certainty.
Unknowns or uncertainties regarding produced water and specific risks related to its treatment and reuse can make decision-making difficult. Strategic advancements in data and analysis are needed to inform risk-based decisions and support the development of reuse programs that are protective of human health and the environment. Produced water can pose challenges in assessing feasible reuse options, including complex chemical character, analytical limitations, variability, and limited applicable permitting or regulatory structures, among others. In order to better support future opportunities for reuse, working collaboratively toward addressing such challenges in the near-term is vital.

Risk-based decision-making concepts can be applied to assist decision-makers in assessing and reducing risks associated with a given reuse scenario.
Incorporating the traditional concepts of risk-based decision-making – research, risk assessment, and risk management – as applied to the unique nature of produced water treatment and reuse, this module presents a conceptual framework designed to assist decision-makers in evaluating a given reuse scenario. GWPC does not intend to prescribe a singular or set process for assessing individual reuse proposals. Instead, GWPC expects this effort to spur discussion, encourage collaboration, promote targeted research, and further multi-stakeholder engagement surrounding this important issue, including refinement of the framework itself.

The phases of the framework include:

- **Phase I: Preliminary assessment of the proposed program** to determine whether the reuse scenario is likely to be feasible and if additional analysis is worth investment. A basic screening compares known characteristics of the produced water to expected water quality needs and reviews, practical considerations such as public perception, regulation, logistics, economics, and benefits, to decide whether the program merits further in-depth analysis.

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- **Phase II: Identification of stressors of interest for treatment and risk analysis.** (A 'stressor' is simply something that can induce an adverse response – in the context of produced water, this might be a constituent of concern or the mixture itself.) This phase has two key objectives: (1) adequately characterizing the produced water to identify stressors of interest that should be targeted for analysis and potential, reduction, or removal; and (2) decision-making and assessment regarding the selection or development of appropriate treatment technologies. The understanding of influent quality, treatment capabilities, and effluent quality narrows the scope of Phase III analysis to priority constituents of concern.
- **Phase III: Risk assessment – treated produced water.** Using knowledge obtained in Phase II, a traditional risk assessment model is applied to treated produced water, to identify risks to human health or the environment that must be reduced or otherwise managed. This phase assesses potential exposure pathways (e.g., through building conceptual site models) and determines whether and at what magnitude a particular constituent or the mixture of treated produced water itself may lead to adverse effects.
- **Phase IV: Risk management and decision making.** Based on the data, tools, and technologies identified in previous phases, an informed decision is reached as to whether and how to move forward with a project, including defining the necessary risk management strategies. It includes a final evaluation of the "practical considerations" of Phase I, a decision on whether the risks as characterized are expected to be manageable, an opportunity to incorporate advanced or additional treatment options, and an effort to implement or develop appropriate risk management strategies, such as quality standards and permit limitations, monitoring tools, best practices, and information sharing. While Phase IV moves toward implementation of a reuse program, it also recognizes the importance of a process of continuous learning and incorporation of new knowledge or tools.

Identifying specific reuse options that address current or emerging needs or drivers in specific regions is an important next step in prioritizing research and development.
Focusing on specific reuse options in specific regions based on the produced water potentially available and need for nearby water users will enable time and resources to be invested in purposeful and actionable research and development with a more defined set of facts and circumstances.

Expanding knowledge and tools for produced water characterization, treatment, risk assessment, and feasibility for reuse is a growing area of focus for research and development.
In addition to substantive discussion regarding research needs related to better characterizing produced water and assessing and managing risks, this module includes an overview of various treatment technologies that exist or are being actively researched. The economic treatment of produced water is a critical step in achieving a feasible project that meets quality objectives, and interest in developing, testing, piloting, or implementing various technologies spans the academic, government, and industrial spaces.

Published literatures is available that can help guide future reuse evaluations.
This module involved a literature review with a defined scope and timeline that identified hundreds of potentially relevant papers and aimed to summarize the types of available texts and learnings at a very high level. In the future, a more targeted literature review may be a useful component of an initial assessment of a particular reuse project or scenario.

Background

The objective of Module 3 is to promote an informed dialogue on current and future reuse of fit-for-purpose produced water outside oil and gas operations. It examines the drivers for reuse and aims to define the information necessary for knowledgeable decision making by regulators, industry, and other stakeholders. It also provides insight on how to fill identified research needs.

Operators and regulators alike are beginning to rethink the economics and long-term sustainability of traditional produced water management practices. While most near-term alternatives focus on recycling produced water for operational uses to reduce fresh water consumption in oil and gas operations (as discussed in Module 2), interest is growing in the potential for produced water reuse outside the oil and gas industry. Unique conditions in oil and gas operations — such as remote locations, dispersed water production, and high salinity levels — have historically made some produced water reuse options difficult to accomplish. In addition to these challenges, produced water reuse potential often comes with complex scientific, regulatory, and policy considerations, specifically with respect to risk management.

Before alternative management strategies can be broadly implemented, a more holistic understanding of the risks and benefits is necessary. This module provides a high-level overview of the types of questions that need to be considered, homing in on components of the research and development (R&D) process for treated produced water reuse outside oil and gas operations. Together with academia, industry, regulators, and non-governmental environmental organizations, GWPC has developed a detailed overview of some top-level considerations and research needs on this subject. The aim of this effort is to identify priority questions or research objectives, and to describe the type of work that may need to be completed by a wide range of stakeholders to answer those questions.

While important questions remain to be addressed, produced water reuse is a subject on which research is rapidly advancing.[98] This module includes a substantive literature review that covers published, peer-reviewed material, referencing other reports where applicable. The review includes selected studies on two types of produced water that are outside the scope of this report: produced water from coalbed methane (CBM) production and from offshore oil and gas production. Because offshore production has historically involved the assessment and permitting of produced water discharges to the ocean, lessons from offshore literature, permits, and practices warrant consideration to inform efforts onshore.

Produced water is not uniform, and neither are the circumstances of its potential treatment and reuse. While some broad research endeavors have value in advancing reuse (i.e., development of more economic treatment technologies; prioritized analytical method advancements), targeted assessments evaluating site-specific reuse options are expected to provide the most value in the near term. This module emphasizes the need to approach produced water reuse challenges and objectives with a fit-for-purpose mindset, meaning that research, treatment decisions, risk management strategies, and in some cases even approval processes should be tailored to address the reuse of a particular produced water for a particular type of reuse. It aims to present a useful framework for identifying and mitigating risks and other considerations as applied to a specific reuse opportunity being considered.

98 One substantive source of information on produced water and available data and literature on its character, treatment, management and other aspects is the USEPA report on "Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States" published in 2016. The report included two relevant chapters on "produced water handling" and "wastewater disposal and reuse" that contain an overview of information available as of writing of the report as well as an overview of data gaps and limitations in EPA's assessment.

The scope of this module addresses produced water from onshore conventional and unconventional oil and gas production. Produced water includes water that flows back during and after the hydraulic fracturing process as well as formation water that returns over the life of a well. Only where it is important to differentiate between these two will this report do so. In most scenarios for discharge or reuse outside the oil and gas industry, the water being considered is most likely the water produced following the initial flowback phase, which would include primarily formation water.

Drivers for Reuse Outside Oil and Gas Operations

Drivers and Opportunities for States and Regulators

All regions of the country have unique characteristics. However, one common thread is the need for safe and adequate water resources to support local and regional needs. Water regulators are often looking for options that can help augment existing resources or slow the drawdown of aquifers or surface water sources without negatively impacting source water or wellhead protection areas. There are several reasons why regional leaders and decision-makers may investigate the role treated produced water may play in meeting water demands.

- **Drought and the demands of expanding populations.** Drought has become an increasing concern for large portions of the United States.[99] The need for an adequate quantity of water for the environment, agriculture, industrial uses and drinking water is vital for public health protection, quality of life, and economic development. This need is particularly pressing where population and development expansion are occurring in regions where water resources are stressed or limited. As discussed in Module 2, reuse of produced water to replace water use in oil and gas operations may increase water resources locally available for other needs like agricultural, industrial, or municipal use. Outside oil and gas operations, produced water may potentially be treated to serve as an adequate substitute for fresh water, though in many cases current research needs to be further advanced to better inform those decisions and address quality and treatment considerations.[100] The use of treated produced water instead of fresh water for some uses may help to locally free

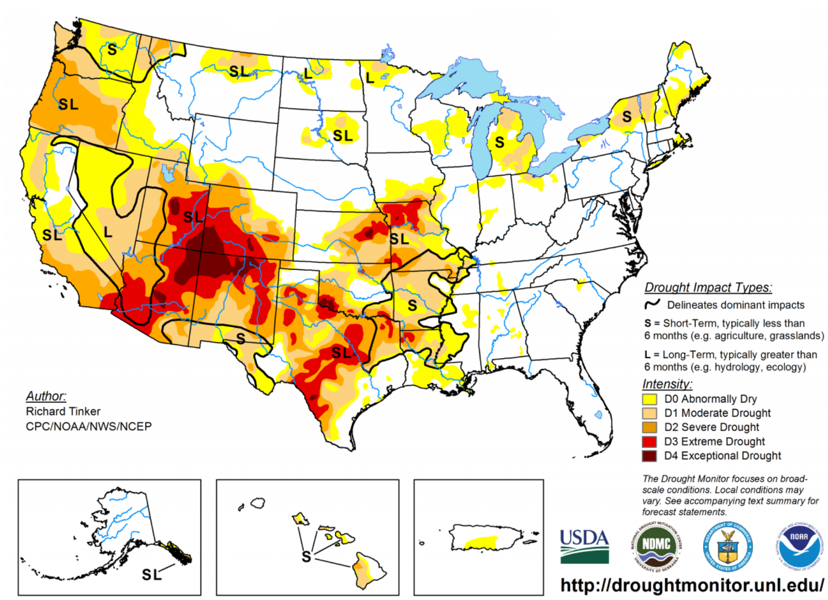


Figure 3-1: Illustration of the Status of Drought across the United States as of August 14, 2018

Source: United States Drought Monitor http://droughtmonitor.unl.edu/

Drought is becoming a pressing concern in regions where population and development expansion are occurring and where water resources are stressed or limited.

99 See *United States Drought Monitor,* https://droughtmonitor.unl.edu/; see also Dennis Mersereau, "Drought Conditions Worsened Across the United States in August," *Forbes* (August 31, 2018), https://www.forbes.com/sites/dennismersereau/2018/08/31/drought-conditions-worsened-across-the-united-states-in-august/#5dc707287842.

100 See, e.g., Alban Echchelh, Tim Hess, and Ruben Sakrabani, "Reusing Oil and Gas Produced Water for Irrigation of Food Crops in Drylands," *Agricultural Water Management* 206:124–34 (July 2018), https://doi.org/10.1016/j.agwat.2018.05.006; José Fernando Martel-Valles, Rahim Foroughbakchk-Pournavab, Facultad de Ciencias Biológicas, Universidad Autónoma de Nuevo León, Adalberto Benavides-Mendoza, and Departamento de Horticultura, Universidad Autónoma Agraria Antonio Narro, "Produced Waters of the Oil Industry as an Alternative Water Source for Food Production," *Revista Internacional de Contaminación Ambiental* 32 (4): 463–75 (2016), https://doi.org/10.20937/RICA.2016.32.04.10.

up potable water resources for higher quality water needs such as drinking water.

- **Fresh groundwater depletion.** In the United States, groundwater is the source of drinking water for about half of the total population, and in 2010, it provided over 50 billion gallons per day for agricultural needs.[101] This heavy reliance on groundwater as source water in areas where groundwater withdrawal occurs at a faster rate than recharge is not sustainable. For example, the Ogallala Aquifer, which spans numerous states, has been severely depleted in the past half century (Figure 3-2). Depletion can reduce groundwater quantity and/or quality; reduce surface water quantity and/or quality in streams, lakes and wetlands where hydraulic connectivity exists; increase pumping costs; increase land subsidence; increase salt water intrusion; and, in some localized circumstances, cause movement of contamination plumes. Where feasible, use of treated produced water or even marginal quality groundwater in place of fresh groundwater could prove beneficial. Additionally, research and treatment could eventually support the utilization of this water in a way that restores certain aquifer volumes, such as through aquifer storage and recovery or managed aquifer recharge, though these alternatives require further analysis.

- **Surface water availability.** As with groundwater depletion, lack of surface water has led numerous municipalities and industries to seek alternative sources of water. Securing safe and reliable alternate sources of water that allow greater conservation of fresh water has the potential to provide increased operational flexibility and better cost management. Fit for purpose produced water could potentially serve as an additional resource option for municipalities or other industries that rely on increasingly limited surface water

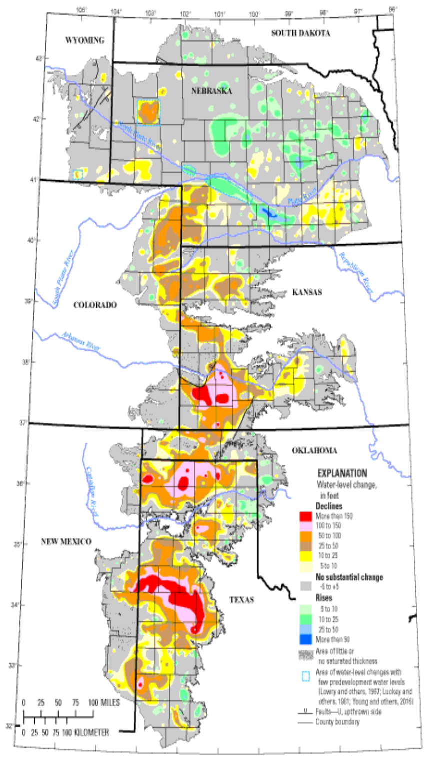


Figure 3-2: High Plains/Ogallala Aquifer Water-Level Changes 1950 – 2015

Source: Virginia McGuire, Hydrologist, USGS

The Ogallala Aquifer, which spans numerous states, has been severely depleted in the past half century.

resources, may be able to restore wetlands negatively impacted by overuse, or could help maintain ecological flows in surface water bodies through treatment and discharge.

- **Induced seismicity.** Disposal of produced water through deep well injection has been the subject of much discussion and study due to the marked increase in the number of earthquakes occurring in some areas of the United States, with many believed to be induced rather than naturally occurring.[102] In some circumstances, this increased seismicity is occurring in areas that are water stressed. Oklahoma is a prime example, where this added pressure on existing produced water

101 Factsheet, American Geosciences Institute, *Groundwater use in the United States* (March 2017), https://www.americangeosciences.org/sites/default/files/CI_Factsheet_2017_2_groundwater_170309.pdf.

102 See, e.g., W.L. Ellsworth, A.L. Llenos, A.F. McGarr, A.J. Michael, J.L. Rubinstein, C.S. Mueller, M.D. Petersen, and E. Calais, "Increasing seismicity in the U.S. Midcontinent: Implications for earthquake hazard," *The Leading Edge* 24(6), 618-622, 622-622, 624-626 (2015), https://doi.org/10.1190/tle34060618.1; K.M. Keranen, M. Weingarten, G. A. Abers, B. A. Bekins, and S. Ge, "Sharp Increase in Central Oklahoma Seismicity since 2008 Induced by Massive Wastewater Injection," *Science* 345 (6195): 448–51 (2014), https://doi.org/10.1126/science.1255802; Won-Young Kim, "Induced Seismicity Associated with Fluid Injection into a Deep Well in Youngstown, Ohio," *Journal of Geophysical Research: Solid Earth* 118 (7): 3506–18 (2013), https://doi.org/10.1002/jgrb.50247.

management strategies, in addition to drought planning, is driving heightened consideration of reuse options.[103]

- **Water planning goals.** Many states are committed to comprehensive or regional water planning studies. As these plans become more inclusive of all water sources rather than the traditional freshwater sources (i.e. shallow groundwater and surface water), it is likely that marginal quality water, produced water, municipal and industrial wastewater, and stormwater will be increasingly considered as potential alternative water sources in the future. To date, most of these plans (where they mention oil and gas development at all) focus on reducing fresh water volumes used in E&P operations. However, some are extending consideration to produced water as a resource for use within the oil and gas industry or potentially available for other purposes. For example, two of the four goals outlined in the water plan for the Red Hills Region of Kansas relate to produced water.[104] Goal three calls for a reduction in the amount of freshwater used in oil and gas completion operations by 4 percent annually and goal four prioritizes work with the oil and gas industry to have 10,000 barrels of fresh water per day replaced with recycled water by 2040. In another example, Oklahoma developed a comprehensive water plan in 2015 that included recommendations for the development of best practices for energy and industry water use and promoted industrial use of marginal quality waters.[105] The plan led to the creation of the Produced Water Working Group (PWWG) to evaluate current practices and potential uses of produced water. The PWWG published a report in 2016 which found that reuse for oil and gas production was the most economical near-term alternative for the state and pointed to treatment costs and other research needs (i.e., toxicological risks, water quality targets, potential beneficial uses) as areas for research and development for the longer term.[106]

Drivers and Opportunities for Industry

As discussed in Module 2, produced water is widely used within the oil and gas industry, both in conventional plays for enhanced oil recovery (i.e., waterflooding) and in unconventional plays for completion activity (hydraulic fracturing), as an alternative to disposal. However, several operational and economic considerations within the oil and gas industry are driving decision-makers to evaluate produced water reuse outside the oil and gas industry as an additional water management option.

- **Limits to reuse in operations.** Over the last decade, the oil and gas industry has made great strides in finding ways to reuse produced water in hydraulic fracturing operations. However, reuse within unconventional plays is likely to have its limits, and this forecast is driving investigation of reuse or discharge opportunities elsewhere. Industry reuse becomes limited as new nearby completions decline, reducing or eliminating the need for water resources for well completion. This can occur when an area is fully developed, or for other reasons, like a commodity price downturn that results in slower development and fewer new completions. In these scenarios, the operator is still generating produced water at active wells but has limited or no nearby operational reuse. When this happens, operators are currently most likely to increase their use of nearby underground injection wells or consider the need for additional disposal wells. Historically, the oil and gas industry has used nearby Class II Underground Injection Control (UIC) wells for disposal of the produced water or has relied on re-injection to produce more oil from water

103 Earthquakes in Oklahoma: What We Know, http://earthquakes.ok.gov/what-we-know/; Oklahoma Water Resources Board, Water for 2060 Produced Water Working Group, https://www.owrb.ok.gov/2060/pwwg.php.

104 Kansas Water Office, Red Hills Regional Advisory Committee Action Plan, https://kwo.ks.gov/about-the-kwo/regional-advisory-committees/red-hills-regional-advisory-committee.

105 The Oklahoma Comprehensive Water Plan, Oklahoma Water Resources Board, http://www.owrb.ok.gov/supply/ocwp/ocwp.php.

106 Report of the Oklahoma Produced Water Working Group (April 2017), http://www.owrb.ok.gov/2060/pwwg.php.

Regional Driver Spotlight: Western Permian Basin. The Delaware Basin, a sub-basin in the western part of the Permian Basin, is unique in the unusually high amount of water produced in the life of a typical well compared to the water used in the completion of the well. The produced water to completion volume is typically 400 to 600 percent. This large volume of produced water may put pressure on disposal capacity. While reuse for oil and gas operations has increased in recent years, the amount of water produced per well exceeds what can be reused on subsequent wells. Reeves County water disposal increased by 94 percent in 15 months from January 2017 to April 2018, as compared to a weighted average for Permian Basin of approximately 20 percent during the same time. If disposal formations become overpressured or seismicity limits new disposal capacity, other options for management such as treatment for discharge may become more viable. Once reuse for completions and UIC disposal is near a limit, the other alternatives could be constructing additional disposal wells, exporting the water to distant areas with UIC disposal capacity, or shutting in wells with the highest water to oil ratio. Recognizing this regional challenge underscores the need to focus attention in the near-term on identifying and answering questions that may arise as new or additional reuse options are considered.

flood operations.[107] However, as the economics and capabilities of advanced treatment technologies improve, there are increasing opportunities to look for other management or reuse options.

- **Limited disposal availability.** Disposal issues vary depending on region and geography. In some places, challenges may arise from pressure imbalances, capacity limits, or induced seismicity-related constraints[108] on available injection and disposal formations, particularly during times when completion and associated flowback activity is high. In other places like Pennsylvania, suitable disposal zones are simply not available or economically accessible and the number of UIC wells are limited. As a result, most produced water is either reused for ongoing operations, trucked long distances to neighboring states for disposal, or, in more limited circumstances, treated for discharge.[109] In such scenarios, where traditional options for produced water disposal are increasingly limited or face significant constraints, the economics of disposal and treatment may change, creating a potential for advanced treatment that had to-date been considered too costly in most parts of the country.[110] Along with looking for ways to expand disposal availability, increased reuse of produced water – within or outside oil and gas operations – may be part of the solution to limited disposal availability in some regions.
- **Economic considerations.** The economics of water use in oil and gas operations can be most simply stated as "how much does it cost to acquire source water and how much does it cost to dispose of produced water or otherwise manage it?" At the beginning of most oil or gas developments, the most economically viable water management strategies are sourcing water locally and disposing of produced water into nearby permitted injection wells, if available, or using it in enhanced oil recovery or waterflood operations. As development in plays continues, infrastructure construction (e.g., pipelines for gathering and transporting produced water, as well as storage and treatment facilities) and increased volumes of produced water make the economics of reuse in subsequent completions more attractive, particularly in circumstances where the cost

107 J.A. Veil, "U.S. Produced Water Volumes and Management Practices in 2012," Ground Water Protection Council, 2015, https://protect-us.mimecast.com/s/sogdC-M89AqcMQXRhw6HwWg?domain=gwpc.org.

108 Stephen Rassenfoss, *SPE Journal of Petroleum Technology* (June 12, 2018), https://www.spe.org/en/print-article/?art=4273.

109 Brian G. Rahm, Josephine T. Bates, Lara R. Bertoia, Amy E. Galford, David A. Yoxtheimer, and Susan J. Riha, "Wastewater Management and Marcellus Shale Gas Development: Trends, Drivers, and Planning Implications," *Journal of Environmental Management* 120 (May 2013): 105–13, https://doi.org/10.1016/j.jenvman.2013.02.029.

110 Report of the Oklahoma Produced Water Working Group (April 2017), http://www.owrb.ok.gov/2060/pwwg.php.

to obtain source water increases. Over time, however, it is possible that disposal capacity and reuse within oil and gas operations may become constrained in some areas, prompting a new set of economic options: investing in new injection and disposal zones, spending more on advanced treatment like desalination to allow reuse or discharge of produced water outside operations, or shutting in producing wells (though the latter option is less likely). With research and development advancements, it is possible that future economics could support large-scale reuse outside oil and gas operations where the water quality and environmental challenges can be met by advanced treatment technologies. This research and development may also take into consideration economic opportunities and co-benefits potentially associated with advanced treatment of produced water, such as recovery of saleable products like salt, heavy brine, iodine, or lithium.

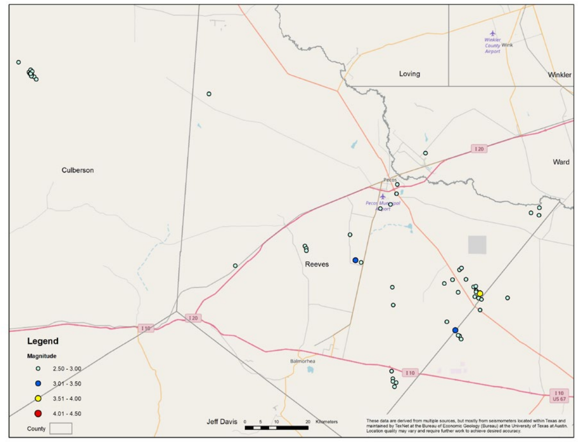


Figure 3-3: TexNet Earthquake Catalog for West Texas, January 1, 2018 – December 31, 2018

Source: http://www.beg.utexas.edu/texnet-cisr/texnet/earthquake-catalog

Induced seismicity related to injection and disposal of produced water is a potential disposal limitation in some regions of Oklahoma, although regulatory action has led to a reduction of this risk. Concerns about induced seismicity also extend to states such as Texas. In the Delaware Basin of Texas, scientists are closely watching an uptick in seismic events. Additionally, in the nearby Midland Basin, ongoing monitoring has detected a pressure change in the San Andres formation, a common disposal zone, and options for disposal may be limited by capacity in the future.

Natural Gas Supply Collaborative: Environmental and Social Performance Indicators. Stakeholders can sometimes drive adjustments in practices or decision-making. For example, the Natural Gas Supply Collaborative (NGSC)—a voluntary collaborative of natural gas purchasers (including Austin Energy, Pacific Gas and Electric, and Xcel Energy, and Consolidated Edison)—published a report in 2017 identifying non-financial performance indicators related to protecting the environment and local communities in the production and supply of natural gas. The report called for reporting on these indicators, a number which relate to water, including:

- Sourcing of water for completions,
- Strategy for managing fresh water use, and
- Strategy for managing water onsite and wastewater.

Relevant leading practices highlighted include:

- Reducing freshwater use through efforts such as wastewater recycling,
- Use of brackish water, and operational improvements;
- Not using local freshwater resources that directly compete with, and negatively impact other, local uses, such as agriculture and drinking supplies;
- Describing how wastewater is handled and its ultimate disposition; and
- Participating in research to better understand opportunities for reuse outside the field and the health and environmental risks associated with reuse, especially for agriculture, prior to its reuse offsite.

For the leading practices, the NGSC referenced similar indicators in other frameworks, including GRI, IPIECA and API. See https://www.mjbradley.com/content/natural-gas-supply-collaborative-0.

Produced Water, Reuse, and Research Needs: Why, When, Where, How?

While there are clear drivers for the reuse of treated produced water outside oil and gas operations, additional considerations must be addressed to understand and mitigate potential risks and promote smart decisions. This section introduces the challenges and opportunities pertinent to decision makers in evaluating new options to reuse of produced water.

Why Is Research Needed?

The potential to beneficially reuse treated produced water outside oil and gas production presents opportunities and prospective benefits for end users, as well as for the oil and gas industry itself. However, challenges associated with produced water may make decisions regarding its reuse complex. Research to address these challenges may be appropriate to support expanded reuse efforts in the future. For example:

- **Analytical challenges and limitations.** Produced waters lack reference materials,[111] essentially a 'control' for a type of sample or mixture, which is either used to calibrate instruments for chemical quantification or to validate methods between labs and estimate error.[112] Some complex waste streams or types of environmental samples also have associated matrix reference materials, which allow analysts to account for chemical or matrix interference from the sample media.[113] The lack of references, as well as produced water variability generally, can pose a challenge in both verifying and standardizing produced water analyses as well as setting the appropriate regulatory goals for new uses.[114] A lack of matrix reference materials is particularly problematic for produced water, which often exhibits matrix interference due to its high salinity. Beyond reference materials, produced water also includes a wide range of constituents for which standard analytical methods (e.g., those that are approved for use in a regulatory context) may not be available. While analysis of treated produced water presents fewer analytical methodology challenges—and therefore fewer method development challenges—there exists a need to demonstrate treated effluent assessment and monitoring is appropriate given an adequate understanding of the constituents in the influent. Identifying priority analytical advancement needs to appropriately assess the quality of produced waters proposed for reuse is a key opportunity moving forward.
- **Quantity of produced water available.** Although some states require volume reporting,[115] widespread available data on produced water volumes is currently limited. In some areas, the large quantity of produced water that may be available could present compelling opportunities for fit-for-purpose reuse.[116] However, absent improved data availability, the amount of produced water available may be difficult to predict[117] and while operators

111 Karl Oetjen, Cloelle G.S. Giddings, Molly McLaughlin, Marika Nell, Jens Blotevogel, Damian E. Helbling, Dan Mueller, and Christopher P. Higgins, "Emerging Analytical Methods for the Characterization and Quantification of Organic Contaminants in Flowback and Produced Water," *Trends in Environmental Analytical Chemistry* 15 (July 2017: 12–23, https://doi.org/10.1016/j.teac.2017.07.002; B. Schumacher, "EPA Analytes and Current Analytical Methods," paper presented at Technical Workshop on Analytical Methods for EPA's Study of the Potential Impacts of Hydraulic Fracturing on Drinking Water Resources, Research Triangle Park, NC, Feb. 25, 2013, https://www.epa.gov/hfstudy/summary-technical-workshop-analytical-chemical-methods.

112 Regina R. Montgomery, "SRM Definitions," NIST, August 11, 2010, https://www.nist.gov/srm/srm-definitions.

113 Janiel J "Measurements and Standards for Contaminants in Environmental Samples," NIST, February 5, 2009, https://www.nist.gov/programs-projects/measurements-and-standards-contaminants-environmental-samples; "Matrix CRMs - Certified Reference Materials (CRMs)." n.d. Sigma-Aldrich, accessed December 17, 2018, https://www.sigmaaldrich.com/analytical-chromatography/analytical-products.html?TablePage=19375153.

114 USEPA, *Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States*, at p. 7-12, (Office of Research and Development: Washington, DC, 2016), EPA/600/R-16/236Fa; see also National Academies of Science, *Workshop Highlights: Flowback and Produced Waters: Opportunities and Challenges for Innovation*, (May 2018), http://nassites.org/uhroundtable/files/2018/05/Produced-Water-Wkshp-Highlights_Final.pdf.

115 For example, California's Public Resources Code §3227 requires quarterly reports on all water produced, injected, and used within oil fields to the Division of Oil, Gas, and Geothermal Resources. Reports are aggregated and made available to the public, https://www.conservation.ca.gov/dog/SB%201281/Pages/SB_1281DataAndReports.aspx.

116 See, e.g., Flannery C. Dolan, Tzahi Y. Cath, and Terri S. Hogue, "Assessing the Feasibility of Using Produced Water for Irrigation in Colorado," *Science of the Total Environment* 640–641 (November 2018): 619–28. https://doi.org/10.1016/j.scitotenv.2018.05.200.

117 Omar J. Guerra, Andrés J. Calderón, Lazaros G. Papageorgiou, Jeffrey J. Siirola, and Gintaras V. Reklaitis, "An Optimization Framework for the Integration of Water Management and Shale Gas Supply Chain Design," *Computers & Chemical Engineering* 92 (September 2016): 230–55 https://doi.org/10.1016/j.compchemeng.2016.03.025; J.A. Veil, "U.S. Produced Water Volumes and Management Practices in 2012," Ground Water Protection Council, 2015, https://protect-us.mimecast.com/s/sogdCM89AqcMQXRhw6HwWg?domain=gwpc.org.

may have good internal volume predictions, that information may not be publishable or accessible. Limited data on produced water volumes and current management strategies also limits the ability to identify pressure points on existing disposal options in advance or to identify volumes that may need other management options, such as reuse. This makes it more challenging to pinpoint areas where targeted near-term research in support of reuse is needed.

- **Quality of produced water.** Published, publicly available research on the chemical and toxicological character of produced water and potential impacts of various reuse scenarios exists, and is growing, but is not extensive (see State of the Science: Literature Review).[118] Limitations in peer-reviewed literature can present a challenge in establishing the appropriate parameters for different reuse options. There has been little historic need to conduct extensive studies to gather this data because traditional disposal methods, like underground injection, come with limited exposure pathways and demand little chemical characterization. EPA's recent study of the hydraulic fracturing water cycle included a review of available publications on characterization of produced water and compiled a table of 599 identified water constituents, though the list was national.[119] Where specific studies do exist, data are often limited to regions where samples are readily available for study, like the Marcellus,[120] and those studies are unlikely to be appropriate for decision-makers to utilize in other regions. Before reuse outside the industry, most produced water will require removal of salts and other dissolved solids, metals and other inorganics, such as ammonia, organics (some at trace levels), and potentially naturally occurring radioactive material (NORM).[121] Quality and other impact considerations lead to important research questions related to decision-making and permitting for reuse and are discussed in-depth later in this module.

- **Variability over time.** Produced water quality[122] and quantity can vary over time and geography. This variability can make decision-making regarding various reuse options complex, posing a challenge not only with respect to permitting and monitoring, but also for business decisions and long-term agreements to take or provide such a water resource. Available produced water volumes are likely to change over time and may only be available in usable quantities for brief periods relative to other resources or an end user's needs.[123] This variability may play a role in decision making by end users that require long-term and consistent volumes versus end users seeking only seasonal volumes. On the other hand, quality variability may also present an opportunity in some regions, where better produced water quality may lend itself to more economical treatment. This is an additional reason why it is critical to understand the efficacy of treatment processes and their ability to robustly manage influent variability.

- **Logistics considerations.** In order to support reuse in other industries or for other purposes outside oil and gas operations, produced

118 See also National Academies of Science, *Workshop Highlights: Flowback and Produced Waters: Opportunities and Challenges for Innovation* (May 2018) (recognizing "significant uncertainty in the chemical composition of produced water"), http://nas-sites.org/uhroundtable/files/2018/05/Produced-Water-Wkshp-Highlights_Final.pdf.

119 USEPA, *Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States*, EPA-600-R-16-236fb, Appendices at E-3 (Dec. 2016).

120 Jenna L. Luek and Michael Gonsior, "Organic Compounds in Hydraulic Fracturing Fluids and Wastewaters: A Review," *Water Research* 123 (October 2017): 536–48, https://doi.org/10.1016/j.watres.2017.07.012.

121 See, e.g., Pei Xu, Jörg E. Drewes, and Dean Heil, "Beneficial Use of Co-Produced Water through Membrane Treatment: Technical-Economic Assessment." *Desalination* 225 (1): 139–55 (2008), https://doi.org/10.1016/j.desal.2007.04.093; Karl Oetjen, Kevin E. Chan, Kristoffer Gulmark, Jan H. Christensen, Jens Blotevogel, Thomas Borch, John R. Spear, Tzahi Y. Cath, and Christopher P. Higgins, "Temporal Characterization and Statistical Analysis of Flowback and Produced Waters and Their Potential for Reuse," *Science of the Total Environment* 619–620 (April 2018): 654–64, https://doi.org/10.1016/j.scitotenv.2017.11.078.

122 Ahmadun Fakhru'l-Razi, Alireza Pendashteh, Luqman Chuah Abdullah, Dayang Radiah Awang Biak, Sayed Siavash Madaeni, and Zurina Zainal Abidin, "Review of Technologies for Oil and Gas Produced Water Treatment," *Journal of Hazardous Materials* 170 (2–3): 530–51 (2009), https://doi.org/10.1016/j.jhazmat.2009.05.044.

123 *Id.* See also Andrew J. Kondash, Elizabeth Albright, and Avner Vengosh, "Quantity of Flowback and Produced Waters from Unconventional Oil and Gas Exploration," *Science of the Total Environment* 574 (January 2017): 314–21, https://doi.org/10.1016/j.scitotenv.2016.09.069.

water will need to be transported from the point of production to the point of treatment and eventually to the point of reuse. This may involve complex logistical considerations, including temporary storage and transport capabilities (e.g., pipelines, trucks) or other potential delivery mechanisms such as discharge or aquifer storage. These logistical considerations can also increase the potential for unintended releases and associated risks.[124] Infrastructure and conveyance decisions will be site or project-specific and the remote nature of many oil and gas production locations may play a role on determining the appropriate mechanism (i.e., surface discharge v. pipeline).

- **Permitting and regulation.** Existing permitting and regulatory structures are in many cases not written with these reuse scenarios in mind, as discussed in Module 1. Where regulatory programs may be required but do not yet exist or require update or modification, collaboration with regulatory bodies to identify appropriate standards will be necessary and should occur early in the decision-making process.

When and Where Should Research Efforts Be Focused?

Some circumstances are likely to lead to discrete scenarios where research on new produced water management options should be prioritized. A substantive evaluation of risks and decision-making on a reuse project may take significant time and resources for operators, end users, and regulators. Understanding where and when to focus these efforts will be vital in ensuring that research is completed in a way that is timely, relevant, and actionable. Examples of scenarios that may call for research prioritization, particularly where more than one of these drivers overlap, include:

- Where produced water volumes are expected to exceed disposal capacity and/or volume demands for recycling in new completions;
- Where high produced water volumes overlap with high volume users of either fresh or saline water or with areas of freshwater scarcity relative to demand;
- Where produced water quality may require less treatment for the designated usage;
- Where projected local water demand exceeds reliable future supply; or
- When other drivers make investment in research, technology, and implementation more realistic or timely.

Identifying when and where research demands prioritization in line with the above examples is an important near-term research need. In some cases, additional data gathering, analysis, and modeling may be useful in identifying specific opportunities.

A logical initial exercise is to determine where areas of significant produced water volumes overlap with localized areas prone to water stress with large-volume users of either fresh or saline waters. A step further might involve a rough characterization of produced water quality relevant to water quality needs for other nearby users. Resulting maps or databases may be able to point to, for example, where high-volume production of a low-TDS produced water overlaps with significant nearby water withdrawals or demands for other uses. This exercise could help to prioritize, at least regionally, where more in-depth research on risks and opportunities for reuse may be most practical and actionable. This recommendation is in line with those of other collaborative efforts. One example is the Colorado Water Resources Institute's Produced Water Workshop in 2006, where a key proposed follow-up action was collaboration with USGS and the Bureau of Reclamation to develop a map highlighting overlap of potentially useable produced water quantities and other factors that could indicate feasibility of use, including infrastructure.[125]

Resources of relevance in prioritizing reuse opportunities could involve a combination of data such as

124 M.A. Engle, I.M. Cozzarelli, Bruce D. Smith, *USGS Investigations of Water Produced During Hydrocarbon Reservoir Development,* Fact Sheet 2014-3104, November 2014, https://pubs.usgs.gov/fs/2014/3104/pdf/fs2014-3104.pdf.

125 Colorado Water Resources Institute and Colorado State University, Produced Waters Workshop (April 4-5, 2006) at v, available at http://www.cwi.colostate.edu/media/publications/is/102.pdf. For the most part, presentations and conversation at the workshop focus on CBM. Other summary recommendations of this group included evaluation of treatment technologies, addressing concentrated wastes, pilot and demonstration projects, and enhanced communication and collaboration.

those included in Figures 3-4 and 3-5. Together, these three data sets illustrate how the factors of water use, produced water availability, and produced water quality could be correlated to determine the most feasible areas/region for further research.

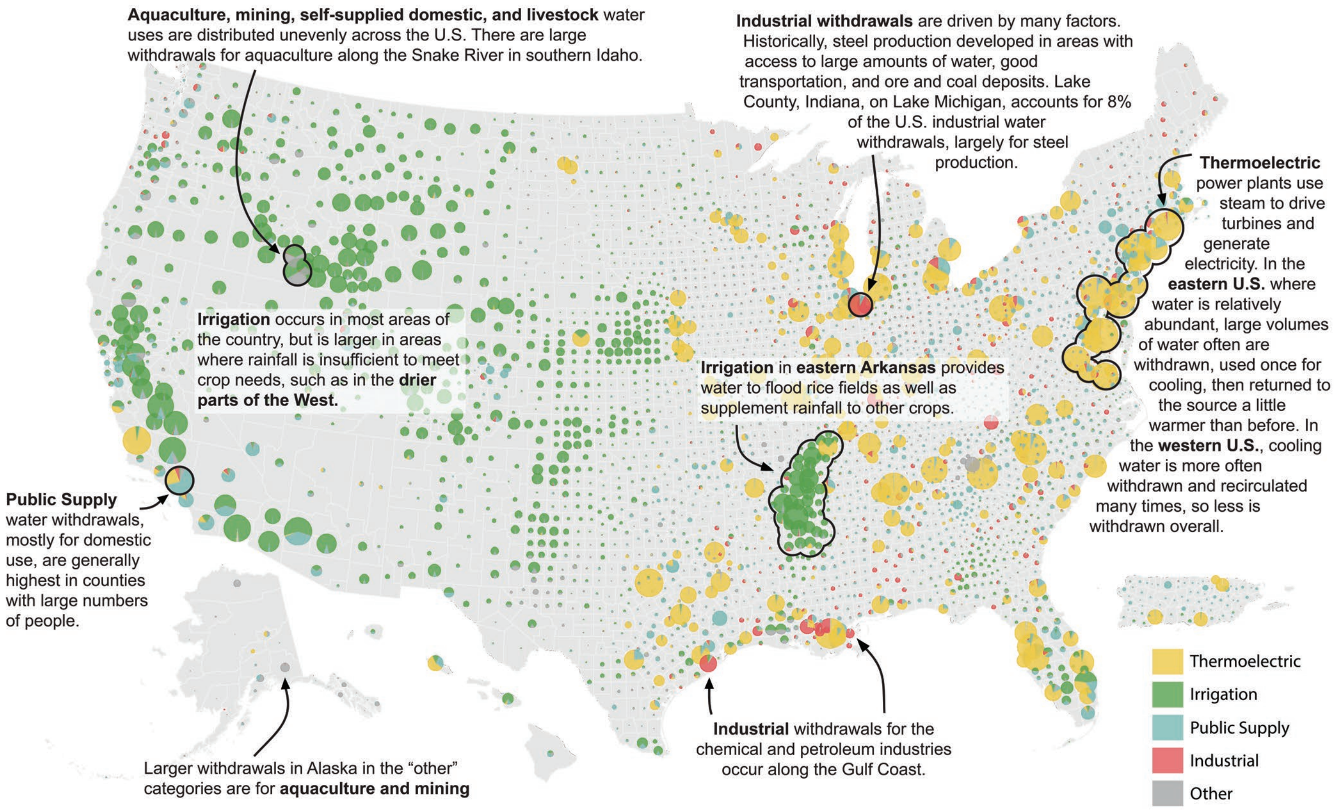
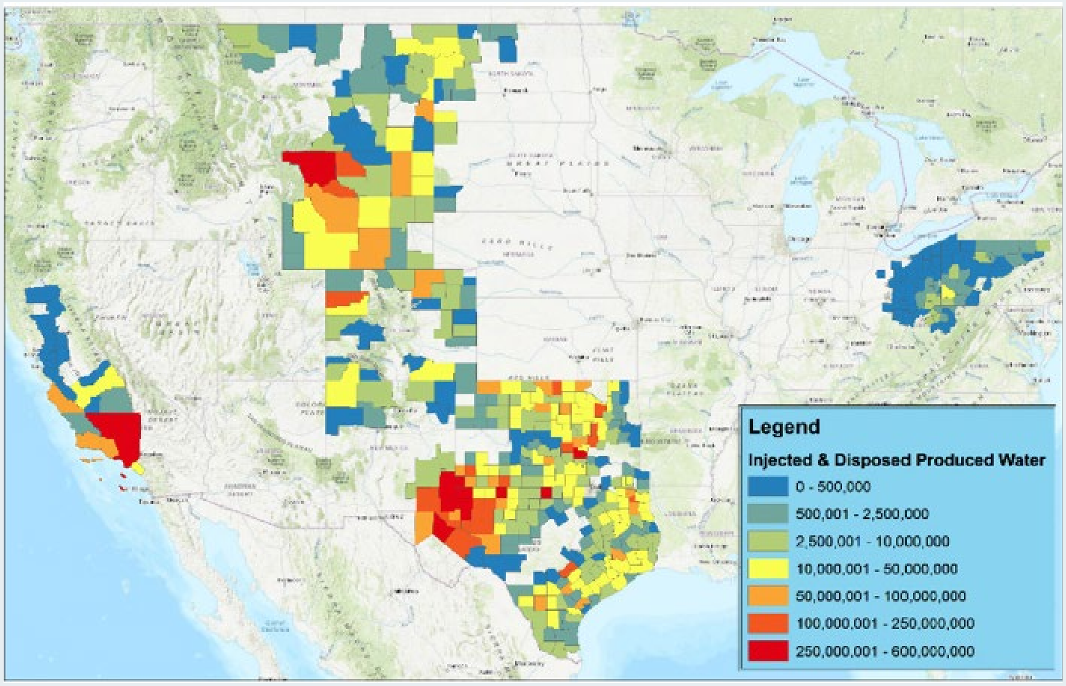


Figure 3-4: Water Use in the U.S., 2015

Source: USGS, https://owi.usgs.gov/vizlab/water-use-15/

Map showing current water withdrawal volumes by user/industry, including fresh and saline water and surface and groundwater, which may be useful in identifying areas where there may be a large water need.



Injected Produced Water by County (bbl.) in 2017 (Figure 2-32)

Produced Water Quality Table (Table 2-4)

	pH		TDS (mg/l)		Calcium (mg/l)		Magnesium (mg/l)		Bicarbonates (mg/l)		Sulfates (mg/l)		Chlorides (mg/l)	
	High	Average	High	Average	High	Average	High	Average	High	Average	High	Average	High	Average
Bakken	7.2	5.9	317,040	270,743	28,184	15,886	2,198	1,164	530	451	1,109	271	195,999	164,756
Central OK	7.4	6.6	162,884	70,547	12,431	3,376	1,955	776	1,076	476	1,502	530	112,348	44,839
Delaware	7.7	6.7	216,319	129,354	17,078	5,892	4,410	1,150	3,410	516	3,060	904	132,995	79,719
DJ/Niobrara	8.3	7.0	74,940	28,238	4,298	574	766	64	1,382	561	2,849	80	51,289	16,470
Eagle Ford	7.6	6.5	82,669	41,999	5,607	2,300	769	341	1,348	378	399	94	56,850	27,893
Haynesville	7.1	5.5	206,835	111,551	21,121	10,470	812	502	590	199	127	13	138,583	68,965
Marcellus	7.2	6.0	315,118	169,177	45,724	15,207	3,626	1,326	345	137	55	11	192,694	108,748
Midland	7.4	6.7	130,841	112,885	29,139	27,059	659	496	753	489	1,292	754	79,293	66,606
Utica	6.5	5.9	288,318	226,590	36,374	26,874	3,398	2,715	230	67	222	23	185,583	145,253

Figure 3-5: Examples of Data on Produced Water Availability and Quality

Source: Figure 2-32 (Module 2, p. 72) and Table 2-4 (Module 2, p. 95)

The map, "Injected Produced Water by County (bbl.) in 2017," shows areas where large volumes of produced water may be available for other uses. The "Produced Water Quality Table," gives basic quality parameters, such as TDS, which could assist in narrowing down locations where TDS is low enough that treatment to meet quality objectives may be more likely to be economical.

One example of this type of effort can be found in a recent study published by the Colorado School of Mines.[126] The research team in this study looked specifically at counties in Colorado, estimating or analyzing produced water volume, produced water quality, irrigation demand, and economic feasibility of treating produced water to irrigation standards (as compared to commercial disposal). The team developed a decision matrix to compare quantity, quality, and demand parameters and then ranked counties to pinpoint optimal locations for potential produced water reuse. After this ranking exercise, six counties were analyzed in-depth and three counties were determined to have water supply, quality, and demand numbers that signal opportunity for reuse. Based on this analysis the researchers concluded that produced water could supply ~3% of the irrigation demand across the six counties studied. While the researchers highlighted this work as an opportunity to look at produced water as a resource, the team also emphasized that decision-makers should consider potential crop uptake of contaminants and degradation of soil quality before deciding to irrigate with produced water.

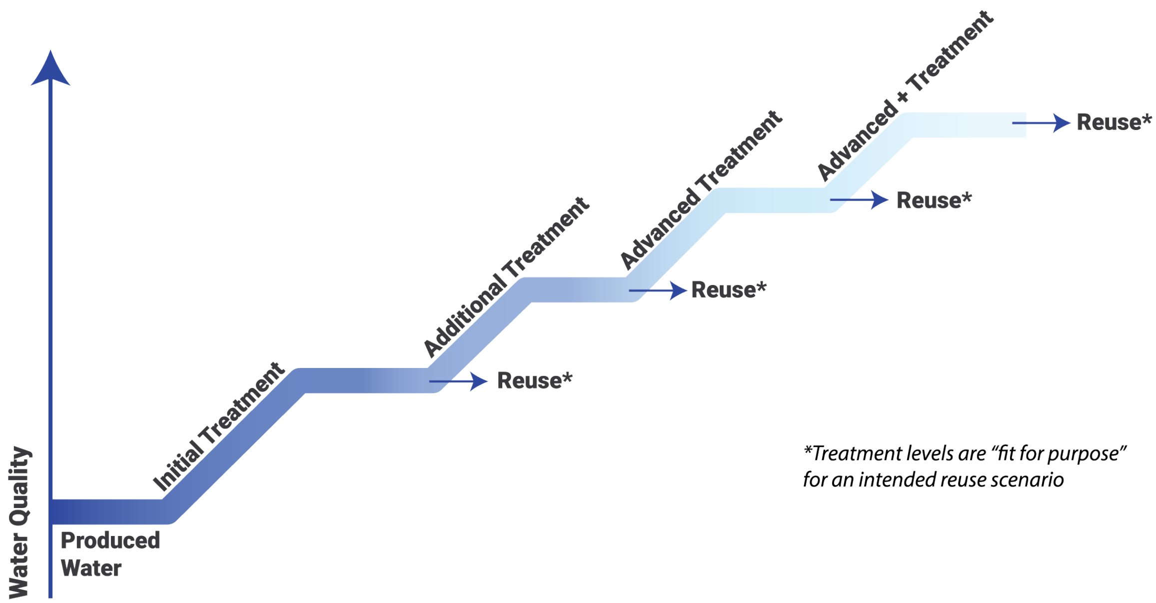


Figure 3-6: The Concept of "Fit for Purpose" as Applied to Levels of Treatment for Different Reuse Scenarios
Source: Adapted and modified from USEPA 2012 Guidelines for Water Reuse

"Fit for purpose" commonly describes the level of treatment applied to a water in order to meet water quality objectives. Treatment technologies can be combined and tailored to fit different objectives.

126 F.C. Dolan, T.Y. Cath, T.S. Hogue, "Assessing the feasibility of using produced water for irrigation in Colorado," *Science of the Total Environment* 640-641 (November 2018): 619-628, https://doi.org/10.1016/j.scitotenv.2018.05.200

FIT FOR PURPOSE

The phrase "fit for purpose" can have multiple meanings. In this module, it signals that the process, action, tool, or technology being discussed is expected to be implemented, utilized, or designed to meet targeted goals unique to the reuse scenario being considered. "Fit for purpose" commonly describes the level of treatment applied to a water in order to meet water quality objectives, as illustrated in Figure 3-5. Treatment technologies can be combined and tailored to fit different objectives.

The same tailored-approach concept is used in this module to refer to research or information gathering objectives as well as risk-management strategies. Depending on the reuse strategy proposed, the questions and considerations involved in identifying and mitigating risks will vary and will also need to be "fit for purpose." Because produced water is highly variable and the range of potential end-use options includes many diverse factors, the "fit-for-purpose" concept is useful to reinforce the need for flexibility and adaptability in evaluating reuse scenarios.

How Should Research Be Conducted?

Any effort to better understand the opportunity to treat and utilize produced water outside oil and gas operations will be greatly advanced through not only applied research, but also strategic collaboration. Where research does occur, it will be vital that groups including academia, industry, and government collaborate to achieve the most substantive and useful results and work toward transparency in communicating and interacting with other interested stakeholders, including the public.

One limitation for studying produced water is researcher access to relevant produced water samples. Some leading institutions focused on this area of work have had success in developing partnerships to obtain a variety of samples. Research is likely to proceed much more quickly and effectively when research labs can partner with industry to expand availability of produced water samples for study. Collaborative identification of specific research goals and coordination among research groups may also help to promote such partnerships and foster the sharing of samples to further investigation of a reuse application or study.

The need for effective and informed decision-making on produced water management alternatives has also prompted collaboration among agencies responsible for oversight. As an example, the State of New Mexico and EPA Region 6 entered into a Memorandum of Understanding[127] in 2018 to investigate the regulatory landscape for produced water reuse. The MOU involves three distinct New Mexico state agencies, as well as both Region 6 and EPA headquarters, who developed a draft white paper aimed at clarifying the permitting and regulatory regime for produced water in the State. The draft white paper became available in November 2018;[128] as of the date of this publication a final has not been published.

127 From https://www.epa.gov/sites/production/files/2018-07/documents/epa-nm-mou_produced-water_07-16-2018.pdf.

128 USEPA Region VI and the State of New Mexico (2018), *Oil and Natural Gas Produced Water Governance in the State of New Mexico* – Draft White Paper, http://www.emnrd.state.nm.us/wastewater/documents/Oil%20and%20Gas%20Produced%20Water%20Goverance%20in%20the%20State%20of%20New%20Mexico%20Draft%20White%20Paper.pdf.

Potential Reuse Scenarios

Several alternative disposal and potential reuse options for produced water are now active or may be considered in the future. Reuse may involve consumption or application to land or discharge to water and may occur in an agricultural, municipal, or industrial setting.

The ideas and examples provided are not exhaustive and represent a subset of reuse applications identified elsewhere, such as in the EPA guidelines for water reuse.[129] Factors impacting feasibility of potential uses (such as logistics, cost, health or environmental risk assessment, regulations, public perception and acceptance, etc.) must be fully considered and will be discussed in later sections.

Many reuse opportunities remain at a conceptual evaluation stage. Where scientific evaluation of risk or other considerations have occurred or are underway, study has primarily been based in laboratories at bench scale or in a limited pilot scale. Field studies are typically costlier and currently less common but can provide real-world data that can confirm opportunities or reveal practical challenges for full-scale implementation.

Reuse options that are active or being tested tend to be in response to localized factors such as:

- Availability of produced water, usually at lower-than-average salinities (and often extracted via conventional production methods or from coalbed methane wells);
- Limited, costly, or nonexistent disposal options;
- Defined need for additional water in the local area;
- Reasonable costs to transport and treat produced water relative to costs of other options for water sourcing or disposal; and
- Appropriate permitting schemes and/or associated regulatory requirements that can be met within the cost framework.

This report identifies three general categories of reuse: (1) land application, (2) water discharges, and (3) industrial uses. Consumption is also included briefly, though limited primarily to the context of livestock or wildlife. Most scenarios will demand some level of treatment and any reuse must meet all applicable regulatory and permitting requirements. Research in support of decision-making should characterize and address associated health and environmental risks.

As projects advance to full-scale application it will be important for all parties to recognize the different terminology that is used in various states or industries. While discharge to a surface water body may be considered a reuse in some circumstances, it may be considered disposal in others. Likewise, land application may be considered disposal under some conditions but in others as a beneficial use for irrigation purposes.

A summary of current literature and previous or ongoing studies on this topic is included in the "State of the Science: Literature Review" section of this module.

Land Application

Several active or potential reuse options center on land application. Produced water may reach land application end users through direct transfer or through other delivery mechanisms such as upstream surface water discharges or aquifer storage projects that increase water available for withdrawal. Most land application scenarios use produced water to replace or supplement fresh water or other brines in (1) irrigation or (2) ice or dust suppression. The levels of treatment for these purposes will vary. This section does not address other mechanisms for land-based disposal such as land farming.[130]

Crop irrigation can range from non-food crops like cotton[131] to food crops for human consumption such as fruit and nut trees. Treated produced water irrigation for crops like hay or livestock feed has not been widely studied but may be in the future. Irrigation could also include municipal use to water

129 USEPA, Guidelines for Water Reuse, (2012), https://www3.epa.gov/region1/npdes/merrimackstation/pdfs/ar/AR-1530.pdf.

130 See, e.g., Texas Railroad Commission, "Landfarms and Land Treatment Facilities," http://www.rrc.state.tx.us/oil-gas/applications-and-permits/environmental-permit-types-information/landfarms-and-landtreatment-facilities/.

131 In 2015, Anadarko and Energy Water solutions partnered with Texas A&M AgriLife Research on a study in Pecos, Texas to investigate irrigation of cotton with desalinated produced water blended with well water (1:4 ratio) as compared to existing well water and also evaluate soil salinity parameters. The study found that that the blend did not reduce cotton yield or lint quality and may improve soil salinity as compared to the well water. https://vpr.colostate.edu/few/wp-content/uploads/sites/14/2016/07/Lewis-TAMU-AGL-NSF-FEW-workshop-12-2015.pdf.

Active Land Application: Crop Irrigation. One example of crop irrigation can be found in the Cawelo Water District, near Bakersfield, California, where produced waters are uniquely low in total dissolved solids and other constituents. Produced water in this region has been treated, blended, and used for irrigation for some time. Recently, studies have been ordered to evaluate chemical exposure and health risks associated with human consumption of the irrigated fruit, vegetable and nut crops.* Regulators have also been given the authority to gather additional information by requiring reporting of all additives used or supplied to operators who operate wells that supply produced water for reuse in order to further inform analysis of the practice.** Public concerns about the use of produced water in agriculture have also prompted the Regional Water Quality Control Board to set up a Food Safety Panel consisting of academics, regulators, and consulting scientists to review the practice, assess risk, and make recommendations in a forthcoming white paper.† More information on this reuse scenario can be found later in this module.

* The California Water Board has a website dedicated to this study that gathers all relevant disclosures, reports, studies, etc. and includes a discussion of the ongoing Food Safety Panel Process. https://www.waterboards.ca.gov/centralvalley/water_issues/oil_fields/food_safety/.

** The authority for the orders is California Water Code §13267.5, which became effective on January 1, 2018. The Water Board has compiled a list of oilfield additives from these reports at https://www.waterboards.ca.gov/centralvalley/water_issues/oil_fields/food_safety/data/2018_0628_additive_info.pdf.

† Food Safety Panel Expert Charter (May 2017), https://www.waterboards.ca.gov/centralvalley/water_issues/oil_fields/food_safety/information/offsep_charter.pdf.

golf courses, road medians, parks, or athletic fields, though this type of use does not appear to have been investigated. The type of irrigation proposed will dictate research and regulatory needs, given that risks to health or the environment will vary depending on the expected exposure pathways and other scenario-specific considerations.

Other land application options include the use of produced water or brine derived from produced water for de-icing of roadways or dust suppression on roads or open land. Roadspreading is one current reuse example where produced water may not be required to be treated (beyond basic separation, settling, etc.) before application, though where allowed most states require some form of chemical characterization to be reported. Various states permit this use, though recent concerns from local communities, regulators, academics, and legislators have led to increased attention and investigation of its utility and potential impacts. Some road application scenarios have proceeded without issue. Pennsylvania is one area with advanced study of this application – studies there have focused on analyzing the produced water used for road application for radiological constituents of potential concern,[132] and others have shown that this application method can result in accumulations of alkali-earth elements (including radium) in soils near roadways.[133] There has also been some indication that produced water may actually be ineffective for dust suppression in some locations.[134] Associated environmental or health risks or consequences have not been fully identified, as the study of this application scenario is ongoing.

132 T.L. Tasker, W.D. Burgos, P. Piotrowski, L. Castillo-Meza, T.A. Blewett, K.B. Ganow, A. Stallworth, et al., "Environmental and Human Health Impacts of Spreading Oil and Gas Wastewater on Roads," *Environmental Science & Technology* 52 (12): 7081–91 (2018), https://doi.org/10.1021/acs.est.8b00716. At least one lawsuit has been filed by organizations in Ohio concerned about radium found in brines approved for use for de-icing and dust suppression in the state. See Don Hopey, "Radium found in commercial roadway de-icing, dust suppression brine," *Pittsburgh Post-Gazette* (July 2, 2018), http://www.post-gazette.com/news/environment/2018/07/02/Radium-radiation-commercial-brine-ohio-pennsylvania-aqua-salina-natures-own/stories/201806260107.

133 K.J. Skalak, et al., "Surface disposal of produced waters in western and southwestern Pennsylvania: Potential for accumulation of alkali-earth elements in sediments," *Int. J. Coal Geology* 126:162-170 (June 2014), https://doi.org/10.1016/j.coal.2013.12.001.

134 Kayla Graber, Christina L.M. Hargiss, Jack E. Norland, and Thomas DeSutter, "Is Oil-Well Produced Water Effective in Abating Road Dust?," *Water, Air, & Soil Pollution* 228:449 (November 2017), https://doi.org/10.1007/s11270-017-3640-x (Graber et al. also emphasized the potential for metals to accumulate in soils near roadways where produced water was applied).

Study or Investigation of Land Application: Crop Irrigation. Researchers from Colorado State University and the United States Department of Agriculture (USDA) collaborated on a greenhouse study investigating the use of treated Denver-Julesburg Basin produced water for irrigation of two salt-tolerant biofuel crops, switchgrass and rapeseed. Researchers evaluated different produced waters with varying total organic carbon (TOC) and total dissolved solids (TDS) levels and relative impacts on seedling emergence, biomass yield, plant height, leaf electrolyte leakages, and plant uptake over one growing season. The research found that higher levels of both TOC and TDS had negative impacts on multiple endpoints, including yield and growth health, and concluded that organic content is potentially a greater quality constraint than salinity. The authors hypothesized that such studies and related findings could inform regulatory decision-making on treatment standards for irrigation. For example, the authors discussed potential optimum treatment levels to at least 3500 mg/L TDS to maintain yield and plant health, removal of organic matter to less than 50 mg/L in order to keep leaf cell damage to less than 50 percent, and a TOC of less than 5 mg/l to keep a "sustainable biomass production rate."*

* Nasim E. Pica, Ken Carlson, Jeffrey J. Steiner, and Reagan Waskom, "Produced Water Reuse for Irrigation of Non-Food Biofuel Crops: Effects on Switchgrass and Rapeseed Germination, Physiology and Biomass Yield," *Industrial Crops and Products* 100:65–76 (June 2017), https://doi.org/10.1016/j.indcrop.2017.02.011.

Some states have conducted their own studies regarding the impacts and appropriate regulatory parameters for land or roadspreading of produced water in response to a number of drivers including community concern. For example, North Dakota conducted a study and implemented new guidelines for use of produced water in de-icing or dust suppression.[135] Similarly, Colorado policymakers are in the process of deciding whether and how to allow or regulate these practices. The Colorado Department of Public Health and Environment developed a report on nationwide practices and risk-related considerations for roadspreading in response to public concern over potential health and environmental impacts.[136] Reconsideration of roadspreading authorization and permitting provisions is also ongoing in Pennsylvania.[137]

REGULATORY VARIABILITY AND ROADSPREADING

Roadspreading is an example that highlights the need for fit-for-purpose risk assessment and use-determination based on different produced water qualities and application circumstances. This variability is reflected in regulatory programs. States differ significantly on their allowance and specific regulation of roadspreading or land application for dust suppression, de-icing, or other purposes. Common regulatory variables can include land owner approval, setbacks, chemical characterization, beneficial use determinations, or limitations on the type of produced water used (e.g., conventional or unconventional; flowback fluids or formation water; TDS level). Some states through either legislation or regulation allow this practice through permitting programs or local ordinances with some specific limitations (e.g., Alaska, Ohio, West Virginia, Wyoming and others) and other states either ban or do not actively permit this use (e.g., Alabama, Idaho, Texas). Pennsylvania has recently halted authorization of this practice.

135 North Dakota, "Guidelines for the Use of Oilfield Salt Brines for Dust and Ice Control," https://deq.nd.gov/Publications/WQ/IceDustControlUsingOilfieldBrine_20130321.pdf.

136 Coady Goodman, *Beneficial Use of Produced Water for Roadspreading: Perspectives for Colorado Policymakers*, University of Colorado – Denver, prepared for the Colorado Department of Public Health and Environment (2017), https://www.ecos.org/wp-content/uploads/2018/08/Coady-Goodman-Beneficial-Use-of-Produced-Water-for-Roadspreading.pdf.

137 Don Hopey, "DEP revokes permission to dump wastewater brine from drilling on dirt roads," *Pittsburgh Post-Gazette*, (May 22, 2018), https://www.post-gazette.com/news/environment/2018/05/22/DEP-brine-prohibited-roadways-pennsylvania-warren-county-gas-oil-drilling/stories/201805220114.

Discharges to Water Bodies

Reuses to replenish water resources may occur through (1) discharge to surface water or (2) injection into subsurface zones. In a vast majority of cases, treatment will be needed prior to surface water discharge or aquifer injection and permitting will be required through federal, state, regional, or local authorities. Where feasibility is determined and risks are deemed acceptable and manageable, the potential benefits of new water volumes may create incentives for advanced treatment for discharge where allowed under current regulations, particularly in western states where a new water source or water rights may have significant economic value.

Whether or not the receiving body is a "Water of the United States" (WOTUS) may determine the applicable regulatory and permitting regime. State definitions of regulated water bodies is also a determining factor. Discharges to surface water can provide an alternative management option for treated produced water or serve specific intended purposes such as agriculture use and wildlife propagation (see, e.g., 40 CFR Part 435, Subpart E), allowing for produced water discharges where it has a use in agriculture or wildlife propagation when discharged). Regulatory considerations are outlined in more detail later in this module.

Another potential water reuse scenario is injection into groundwater for near-term or future use (known commonly as aquifer storage and recovery or ASR, or managed aquifer recharge). A clear example of this use has not been identified in literature reviewed for this report, though there may be interest in this option in the future with further study into treatment technologies as well as health and environmental risks, particularly as it may allow for long-term, large-volume storage of treated water. Preserving the quality of groundwater is a key objective for this reuse option.

Treated produced water has been proposed by at least one study for streamflow enhancement and ecosystem services,[138] although treatment to suitable water quality standards would be a key consideration for this use and could be expensive. Treated produced water also could be used to prevent salt water intrusion in coastal regions or to address subsidence or compaction in oil producing regions. Two articles on such uses have been identified.[139]

Industrial Applications

Some industrial applications may prove feasible as reuse options for produced water, which may or may not require treatment, including (1) replacement of a fresh, saline, or otherwise degraded water or feedstream for an industrial process and (2) mining, processing, or manufacturing of other products from the treatment of produced water for sale or use. Feasibility will depend on such considerations as geographic proximity, economics, and policy and regulation, as well as appropriate risk analysis. Where exposure pathways are limited, quality requirements necessary to prevent ecosystem or health impacts may be reduced in an industrial context as compared to other applications, though this proposition should be further investigated. Most examples provided below are in research phases and have not been actively applied to date.

Seawater and brackish water have been used since the 1970s in some coastal locations as once-through cooling water in power-production cooling towers. This application may be a potential reuse option for treated produced water, though further investigation regarding the impacts on the industrial process itself as well as implications for eventual discharge requirements remains necessary. Treatment of saline and CBM waters for these types of uses has been investigated in several studies.[140] Despite the potential for corrosion and scale deposition, there may be an

138 See, e.g., H.N. Bischel et al., "Renewing Urban Streams with Recycled Water for Streamflow Augmentation: Hydrologic, Water Quality, and Ecosystem Services Management," E*nvironmental Engineering Science* 30 (2013).

139 See, e.g., X.C. Colazas, R.W. Strehle, in *Developments in Petroleum Science*, G.V. Chilingarian, E.C. Donaldson, T.F. Yen, Eds. (Elsevier, 1995), vol. 41, pp. 285-335; I. Khurshid, Y. Fujii, J. Choe, "Analytical model to determine optimal fluid injection time ranges for increasing fluid storage and oil recovery: A reservoir compaction approach," *J. Petroleum Science and Engineering* 135, 240-245 (2015); EPA, 1999b, "The Class V Underground Injection Control Study, Volume 23, Subsidence Control Wells," EPA/816-R-99-014w, U.S. Environmental Protection Agency, Sept. http://www.epa.gov/safewater/uic/class5/pdf/study_uic-class5_classvstudy_volume23-subsidencecontrol.pdf; M.N. Mayuga and D.R. Allen, "Subsidence in the Wilmington Oil Field, Long Beach, California, USA," IAHS-AISH Publication 88 (1969).

140 S. Altman, et.al., "Nanofiltration Treatment Options for Thermoelectric Power Plant Water Treatment Demands," Sandia National Laboratories, SAND2010-3915 (2010); NETL, "Use of non-traditional water for power plant applications: An overview of DOE/NETL R&D efforts, Pittsburgh, PA," Department of Energy, National Energy Technology Laboratory: 85 (2009); J.H. Rodgers and J.W. Castle, "An Innovative System for the Efficient and Effective Treatment of Non-traditional Waters for Reuse in Thermoelectric Power Generation," (Clemson University: 2008), U.S. DOE Award # DE-FG26-05NT42535; P. Kobos, *Combining Power Plant Water Needs and Carbon Storage using Saline Formation: An Assessment Tool*, Eighth Annual Conference on Carbon Capture and Sequestraton-DOE/NETL, Pittsburgh, PA, 2009.

economic and water conservation case to be made for reuse in fresh-water-scarce locations[141] if produced water can be treated to meet necessary process and permitting requirements.

Potential Industrial Applications. Researchers have presented technical and economic analyses of theoretical produced water use in cooling for the San Juan Generating station in northwestern New Mexico.* Others have investigated use for boiler makeup water in industrial plants,** though this application would require desalination at a minimum. Another hypothetical use of produced water is as a replacement for other water sources in Class III UIC solution mining, a process used to recover minerals from deposits. For example, potash mines in southeastern New Mexico use saline water in ore processing. Some mines also use salt water brines for solution mining. In theory, treated produced water from the nearby Permian Basin could be an alternative source of water for mine processing, although local economics, supplies, and logistics among other appropriate considerations would dictate feasibility.

* M. N. DiFilippo, in *Advanced Coolng Technologies EPRI Workshop.* (2008). J. S. Maulbetsch, M. N. DiFilippo, paper presented at the Once-Through Cooling: Results Symposium, University of California, Davis, California, January 16, 2008.

** H. Bill, X. Xie, D.-c. Yan, New technology for heavy oil exploitation wastewater reused as boiler feedwater. *Petroleum Exploration and Development* 35, 113-117 (2008).

Produced water containing large amounts of salts and minerals could be a useful source for extraction. Chemicals that may be extracted in economically useful quantities in theory include gypsum, sodium chloride, magnesium chloride, magnesium sulfate, bicarbonate, bromide, iodine, lithium salts, potassium salts, and metals such as copper. Generating valuable byproducts has the potential to enhance economic feasibility of advanced produced water treatment to meet water quality requirements for other produced water reuse scenarios. There is also interest in extracting rare earth elements, though practical and economic feasibility of this process has not yet been extensively demonstrated.[142]

Produced water could also be a source of brine for chemical synthesis, including acids or alkalis (caustic soda or bases). While testing of brackish water concentrate for these purposes (similar salinities to produced water in some regions) has moved into commercial development,[143] use of produced water itself as an industrial chemical source remains theoretical. The chemistry of produced water is much more complex and as such may prove less cost effective due to additional treatment requirements.

Use of produced water in algae cultivation for biofuels and coproduct generation has been identified as a future potential reuse. Because this option does not release produced water outside lined cultivation ponds, no discharge permit would be required.[144]

AGRICULTURAL AND WILDLIFE USES

The reuse of treated produced water for agriculture or wildlife purposes actively occurs in some areas of the country today and is a primary consideration in many options proposed for the future. The guidelines and permitting policies regulating these uses are discussed both in Module 1 and the regulatory section immediately below.

Delivery for reuse of treated produced water in irrigation, agriculture, or for wildlife can occur via a variety of means including surface water discharge for downstream use, direct conveyance, or injection into an aquifer for later reuse. Often, produced water is used or being actively considered for these purposes where other sources of water are stressed or limited. The considerations included in this module to advance understanding of treated produced waters and identify and mitigate any potential risks from reuse for health and the environment should inform decision-making on this type of use as well as others.

141 M. H. Sharqawy, J. H. Lienhard, S. M. Zubair, On Thermal Performance of Seawater Cooling Towers. *ASME J. Eng. Gas Turbines Power* 133, 043001—043007 (2010).

142 See e.g., N., Ghahremani, Y. Gamboa, L. Camacho, and L. Clapp, "Measurement of Rare Earth Element Concentrations in Produced Water from the Eagle Ford Shale," Abstract and Poster Presented at 66th Annual GCAGS Convention and 63rd Annual GCSSEPM Meeting in Corpus Christi, Texas, September 18-20, 2016. Abstract available at http://www.gcags.org/exploreanddiscover/2016/00122_ghahremani_et_al.pdf.

143 For example, http://envirowaterminerals.com/projects.html.

144 See e.g., "Final Report, National Alliance for Advanced Biofuels and Bioproducts (NAABB) Synopsis," U.S. Department of Energy, Energy Efficiency and Renewable Energy Program (2014); E. J. Sullivan Graham et al., "Oil and gas produced water as a growth medium for microalgae cultivation: A review and feasibility analysis," *Algal Research* 24, 492-504 (2017); Thomas C. Hopkins et al., "Effects of salinity and nitrogen source on growth and lipid production for a wild algal polyculture in produced water media," *Algal Research* 38 (2019), https://doi.org/10.1016/j.algal.2018.101406.

Regulatory Studies, Examples, and other Permitting Considerations for Reuse

Module 1 of this report provides a substantive overview of the current regulatory environment related to produced water management, disposal, and reuse. This section highlights additional regulatory studies, potential permit provisions, water quality standards, and other considerations specific to reuse or discharge outside of oil and gas operations. The intent is not to provide an exhaustive overview of state and federal provisions that related to produced water reuse, but rather to present examples highlighting the range of ongoing or potential regulatory considerations that have or may come into play.

EPA Study and Regulation of Oil and Gas Discharges

While most governance related to water and oil and gas occurs at the state or local level, the EPA's Clean Water Act (CWA) authority has implications for surface water discharges, namely through the National Pollutant Discharge Elimination System (NPDES) permitting program. The baseline CWA regulations that specifically apply to produced water date back to rules passed in the 1970s (e.g., effluent limitation guidelines (ELG) for the oil and gas extraction point source category, 40 CFR pt. 435 (41 Fed. Reg. 44942 (Oct 13, 1976); 44 Fed. Reg. 22069 (April 13, 1979)). However, in recent years the EPA has devoted significant time and resources into further studying both treated and untreated produced water and discharge practices and regulations – building on outcomes and findings of earlier studies to inform more active and directed investigations today. Efforts include:

- **Study of oil and gas extraction wastewater management** (2018-2019): In 2018, EPA launched an effort to engage with states, tribes, and stakeholders to consider available approaches to manage produced water at onshore facilities. EPA staff consulted with state, industry, academic, and NGO representatives across the country on a variety of issues related to produced water management and potential discharges under the NDPES program from all potential sites and facilities.[145] In October of 2018, EPA held a public meeting to take further comment and share the results of their study to-date.[146] A white paper on the effort is expected in 2019 and will inform EPA decision-making on whether to revisit the existing regulatory programs for discharge of oil and gas extraction wastewater.
- **Centralized waste treatment** (2014 – 2017; published May 2018): Discharges of treated produced water may occur through centralized waste treatment (CWT) facilities offsite from oil and gas operations under industrial effluent limitation guidelines in 40 CFR pt. 437 (65 Fed. Reg. 81300 (Dec. 22, 2000)), though EPA has indicated in the past that these standards were not written with produced water in mind.[147] In 2018, EPA published a study of facilities historically and currently accepting oil and gas produced waters under the CWT effluent limitation guidelines (40 CFR pt. 437).[148] EPA's report provided detailed analysis in a number of areas of interest: identification of CWT facilities that accept oil and gas extraction wastes (including produced water); regulatory status and permitting of facilities; characteristics of wastewaters; applicable treatment technologies and their costs and performance; economic and financial characteristics of the CWT industry; documented and potential human health and environmental impacts of discharges; and generation and management of treatment residuals and transfer of pollutants to other media (like solid wastes and air emissions). The report demonstrated that CWTs can be a viable option for produced water treatment and discharge and that the necessary treatment technologies can be cost-competitive under certain circumstances. However, EPA also made a number

145 USEPA, *Study of Oil and Gas Extraction Wastewater Management*, https://www.epa.gov/eg/study-oil-and-gas-extraction-wastewater-management#public-meeting (last visited Oct. 21, 2018).

146 EPA Presentation – Oil and Gas Study (October 9, 2018), https://www.epa.gov/eg/oil-and-gas-extraction-wastewater-management-study-documents.

147 Memorandum from James Hanlon, Director of EPA's Office of Wastewater Management to the EPA regions on Natural Gas Drilling in the Marcellus Shale under the NPDES Program, Attachment: NPDES Program Frequently Asked Questions (March 16, 2011), https://www3.epa.gov/npdes/pubs/hydrofracturing_faq.pdf.

148 USEPA, *Detailed Study of the Centralized Waste Treatment Point Source Category for Facilities Managing Oil and Gas Extraction Wastes*, EPA-821-R-18-004 (May 2018), https://www.epa.gov/sites/production/files/2018-05/documents/cwt-study_may-2018.pdf.

of findings that highlighted challenges of the CWT program as applied to produced water – including treatment cost, lack of standards designed for produced water, analytical challenges, facilities with inappropriate technologies that may discharge pollutants of concern, solid waste management challenges, and recorded impacts of existing or historic discharges. The Executive Summary of EPA's report is included in Appendix 3-A.

- **Hydraulic fracturing study** (2010 – 2015; published December 2016). In 2016, EPA finalized a broad study of potential drinking water impacts from the 'hydraulic fracturing water cycle' that included water-related considerations from acquisition to disposal, not just for hydraulic fracturing itself. In the report's Executive Summary, EPA identifies activities that may result in impacts to drinking water, including the "discharge of inadequately treated hydraulic fracturing wastewater to surface water resources."[149] This observation reinforces the importance of ensuring adequate treatment to meet applicable water quality criteria in reuse scenarios involving discharges to surface waters that may serve as drinking water supplies.
- **Pretreatment standards for the oil and gas extraction point source category** (Final, June 28, 2016): In 2016, EPA finalized a rule that prohibits indirect discharges of produced water from unconventional oil and gas operating facilities through publicly owned treatment works, or POTWs.[150] Recognizing some challenges related to its definition of unconventional and conventional, particularly in relation to ongoing practices in Pennsylvania, EPA extended the compliance deadline for the affected facilities with a December of 2016 amendment.[151]

The 98th meridian

While onshore effluent limitation guidelines generally prohibit the discharge of pollutants from oil and gas extraction facilities, there is a key exception that was written for more arid, western states. Subpart E of 40 CFR Part 435 applies to onshore facilities west of the 98th meridian for which "the produced water has a use in agriculture or wildlife propagation when discharged into navigable waters" (40 CFR §435.50). EPA defines that phrase further to mean that "produced water is of good enough quality to be used for wildlife or livestock watering or other agricultural uses and that the produced water is actually put to such use during periods of discharge" (40 CFR §435.51(c)) and the associated effluent limitation is a 35 mg/L daily maximum for oil and grease (§435.52(b)).

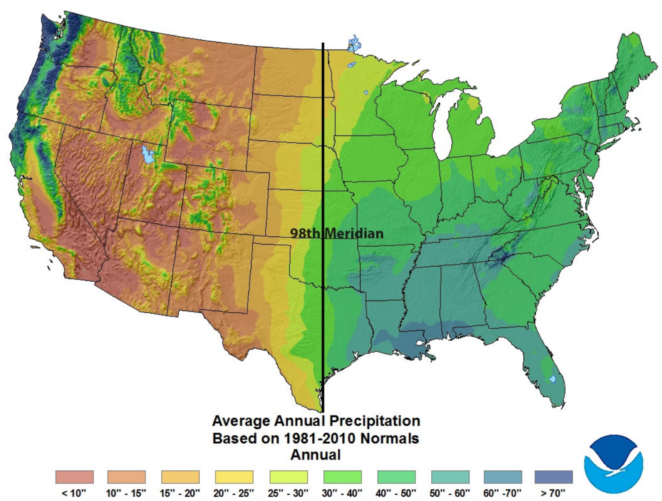


Figure 3-7: Map Showing 98th Meridian Overlain on Annual Precipitation Map

Source: Modified from NOAA https://www.ncdc.noaa.gov/climateatlas/

149 USEPA, *Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources in the United States – Executive Summary*, EPA-600-R-16-236ES at 2 (Dec. 2016).

150 81 Fed. Reg. 41857 (June 28, 2016); see also USEPA Fact Sheet: Pretreatment Standards for the Oil and Gas Extraction Point Source Category (June 2016), https://www.epa.gov/sites/production/files/2016-06/documents/uog-final-rule_fact-sheet_06-14-2016.pdf.

151 Effluent Limitation Guidelines and Standards for the Oil and Gas Extraction Point Source Category – Implementation Date Extension, 81 Fed. Reg. 88127 (Dec. 7, 2016).

The decision on what constitutes "good enough quality" and satisfactory representation that the appropriate uses are in place to qualify for coverage under this ELG is left to the permitting authority. There is no publicly accessible compilation on the number of permits issued under this ELG or the volumes discharged. However, some states, and in some cases the appropriate EPA Region, have issued individual or general permits for discharges west of the 98th meridian.

Examples include:

- **Colorado general permit.** The Colorado Department of Public Health and Environment established a General Permit (permit No. COG-840000) for Discharges Associated with Produced Water Treatment Facilities.[152] The permit takes into consideration not only the 40 CFR Part 435, Subpart E ELG, but also other Colorado regulations, and state water quality numeric and narrative standards. While some discharge and monitoring requirements are established in the permit, including a 3500 mg/L TDS 30-day average, constituents such as radium, organics, or other radionuclides, as deemed necessary, can be established on a case by case basis. The permit also establishes quarterly acute and chronic Whole Effluent Toxicity (WET) testing requirements.
- **California produced water discharge – Pismo Creek.**[153] The Arroyo Grande Produced Water Reclamation Facility produces reclaimed water via treatment of produced water from nearby oil wells. The water may include flow from above or below the hydrocarbon zone or flow from an injection recovery facility. The facility utilizes two phases of treatment. The first phase consists of warm-lime softening, microfiltration to remove particulates, strong-acid cation softening, and cooling of the produced water. Miscellaneous plant wastewater is incorporated into the waste stream before the beginning of the second phase. The second phase of treatment includes a two-pass reverse osmosis (RO) system, weak-ion exchange ammonia (NH_3) removal, chemical polishing, storage, cooling, and aeration. The treated water goes to irrigation use, while unused treated water is discharged into nearby Pismo Creek, with volumes not to exceed 0.84 million gallons per day (MGD). That discharge is regulated by a National Pollutant Discharge Elimination System (NPDES) permit, which must be renewed every five years and is subject to the technology-based effluent limitations established for discharges west of the 98th meridian under 40 C.F.R. Part 435 Subpart E.

  As part of the initial permitting process, the facility owner submitted documentation that the discharge contributes to recharging groundwater used for agricultural purposes downstream. Additionally, the facility submitted documentation stating that the discharge will contribute to recharging groundwater in a manner that will help prevent and/or reduce potential seawater intrusion. The regulatory agency has concluded that discharged water quality is adequate to support wildlife in and around Pismo Creek, and monitoring and reporting requirements are included in the permit to provide monthly compliance data.
- **Wyoming application for permit to surface discharge produced water (short form C).** In September of 2018 the Wyoming Department of Environmental Protection updated its application for a permit for surface water discharges of produced water (see Appendix 3-B). In addition to basic outfall information, the application requires a description of measures to prevent access to ponds from grazing animals and birds, treatment and control measures to meet standards and prevent erosion, and a list of all potential pollutants expected to be in the discharge. Lab analysis and reports for water proposed for discharge is required for 35 parameters with required detection limits. Examples of the standards

152 CDPS General Permit for Discharges Associated with Produced Water Treatment Facilities No. COG-840000 https://www.colorado.gov/pacific/sites/default/files/WQ%20COG840000%20PERMIT_0.pdf. The permit was modified in January 2012 and expired on August 31, 2014. There is no set date for a planned renewal of the permit, though it is considered "administratively continued." See https://www.colorado.gov/pacific/cdphe/wq-general-permit-work-plan-schedule.

153 Provided by experts at the California Central Valley Regional Water Quality Control Board.

for discharge of certain constituents include barium (2000 ug/L), boron (5000 ug/L), chloride (2000 mg/L or 230 mg/L for higher water classes), Radium 226 (5 or 60 pCi/L), and TDS (5,000 mg/L). The permittee must also provide documentation that the produced water will be used for agriculture or wildlife during periods of discharge for each outfall in the application.

COALBED METHANE

Coalbed methane (CBM) produced water discharges are not covered at length in this report. It is common, however, to see CBM produced water discharges discussed in conjunction with the 98th meridian regulatory provisions because such discharges are still subject to NPDES statutes and provisions. However, while EPA historically considered establishing ELGs for the CBM industry, EPA decided to delist CBM and did not pursue development of specific national ELGs. See Coalbed Methane Extraction Industry, USEPA, https://www.epa.gov/eg/coalbed-methane-extraction-industry.

Role of state standards

Federal standards are not the only standards that are of importance in the consideration of various reuse scenarios. For example, as made clear by the 98th meridian discussion above, discharges to surface waters will also have to incorporate applicable state water quality narrative or numerical standards and any other requirements deemed necessary by the permitting authority. The interpretation of the anti-degradation provision of the water quality standards will also be important since this could preclude the addition of a contaminant even if there is no impairment. There may be a need to develop new or modified water quality standards where new or changing practices for produced water reuse or discharge are proposed or implemented. While revisiting existing standards (including those that may make certain uses impractical or impossible) may present an opportunity to expand options for produced water reuse, the development of new standards may also present challenges in some cases due to the need for expanded research, data, or analytical tools. State permits and decision-making on reuse may also consider a variety of standards, guidelines, permits, or other best practices that relate to a specific end use being considered, such as quality standards for livestock watering.

Historically, states have limited their study and regulation of produced water to more traditional management practices or spill remediation. For example, in the late 1980s, Ohio conducted a study to collect better data on trace metals in brine to better understand potential for water contamination, including from the use of brine for ice control.[154] Some states have recently adopted new programs or regulations that specifically address reuse of produced water. Many of these aim to further recycling of produced water for reuse in oil and gas operations are discussed in Module 2. Some standards have also had implications for treatment goals at centralized facilities. For example, Pennsylvania's WMGR123 is a general permit for the processing and beneficial use of oil and gas liquid waste to develop or hydraulically fracture an oil or gas well.[155] Treatment to meet the standards in Appendix A of WMGR123 effectively allows for treated water to be "dewasted" by definition, and as such transported and stored under the same standards as fresh water. Some CWT facilities in Pennsylvania treat to meet this standard as well as the discharge permit standards in order to provide dewasted water to operators for reuse. The WMGR123 permit also incorporates a Pennsylvania Water Quality standard for TDS established specifically for "new and expanding treated discharges of wastewater resulting from fracturing, production, field exploration, drilling or well completion of natural gas wells."[156] The new water quality standard allows authorization of discharges only from CWTs or from POTWs after treatment at a CWT, and establishes monthly average limits of 500 mg/L TDS; 250 mg/L total chlorides; 10 mg/L total barium; and 10 mg/L total strontium.[157]

Appendix A from Pennsylvania's WMGR123 permit is included below (Table 3-1), listing the treatment standards for a set group of constituents.

154 Norman F. Knapp and David A. Stith, *Characterization of Trace Metals in Ohio Brines*, Open File Report 89-1.

155 PA WMGR123, Processing and Beneficial Use of Oil and Gas Liquid Waste (Amended March 14, 2012; Expires October 4, 2020), See http://files.dep.state.pa.us/Waste/Bureau%20of%20Waste%20Management/WasteMgtPortalFiles/SolidWaste/Residual_Waste/GP/WMGR123.pdf.

156 25 PA. Code §95.10(b)(3).

157 *Id.* at §95.10(b)(3)(i) – (vii).

Table 3-1: Pennsylvania WMGR123 Appendix A: Maximum Concentrations – Derived from Drinking Water Standards, Water Quality Standards for Rivers and Streams, and Typical Values Observed in Fresh Water Rivers and Streams (reformatted)

Constituent	Limit	Constituent	Limit
Aluminum	0.2 mg/L	Manganese	0.2 mg/L
Ammonia	2 mg/L	MBAS (Surfactants)	0.5 mg/L
Arsenic	10 µg/L	Methanol	3.5 mg/L
Barium	2 mg/L	Molybdenum	0.21 mg/L
Benzene	0.12 µg/L	Nickel	30 µg/L
Beryllium	4 µg/L	Nitrite-Nitrate Nitrogen	2 mg/L
Boron	1.6 mg/L	Oil & Grease	ND
Bromide	0.1 mg/L	pH	6.5-8.5 SU
Butoxyethanol	0.7 mg/L	Radium-226 + -228	5 pCi/L (combined)
Cadmium	0.16 µg/L	Selenium	4.6 µg/L
Chloride	25 mg/L	Silver	1.2 µg/L
COD	15 mg/L	Sodium	25 mg/L
Chromium	10 µg/L	Strontium	4.2 mg/L
Copper	5 µg/L	Sulfate	25 mg/L
Ethylene Glycol	13 µg/L	Toluene	0.33 mg/L
Gross Alpha	15 pCi/L	TDS	500 mg/L
Gross Beta	1,000 pCi/L	TSS	45 mg/L
Iron	0.3 mg/L	Uranium	30 µg/L
Lead	1.3 µg/L	Zinc	65 µg/L
Magnesium	10 mg/L		

Regulatory authority

Questions are likely within a state and between state and federal authorities in order to clarify the regulatory authority or authorities for a certain end use. Within a state, some agencies that may not traditionally deal with oil and gas operations may need to be consulted or advised regarding new reuse scenarios for produced water. This might include agencies such as the water quality divisions, waste divisions, departments of transportation, fish and wildlife, agriculture, or others. In addition, where regulatory authority is not already clarified in statutes, a state's department of environmental quality (or other environmental, health, and natural resource agencies) and oil and gas agency may need to establish clear authorities for produced water reuse and/or introduction to water bodies (e.g., discharges to surface water or, injection into aquifers or infiltration to ground water). Similar clarification exercises may be appropriate between a state and the EPA, particularly where a state may not have primacy to implement certain statutes under the Clean Water Act.

An example of such an initiative is the state of New Mexico and EPA Region VI Memorandum of Understanding to clarify the regulatory structures and roles for produced water in New Mexico.[158]

Finally, local authorities cannot be forgotten. Parties seeking to pursue produced water reuse projects should work to understand and build relationships with local and county governments or other local leaders and decision-makers, including landowners and other stakeholders. State and federal requirements are often the minimum that must be met, and local authorities who work to protect local interests can have significant impacts on the success of a project.

158 The MOU and Press Release can be found at https://www.epa.gov/newsreleases/epa-signs-mou-new-mexico-explore-wastewater-reuse-options-oil-and-natural-gas-industry or https://www.epa.gov/uog/memorandum-understanding-between-state-new-mexico-and-epa-governance-produced-water-new-mexico.

Legislative Efforts and Impacts on Reuse Decisions. Legislation can also have an impact on reuse research and practices. For example, in 2002, the New Mexico Legislature passed a limited-term bill intended to promote treatment and discharge of produced water to the Pecos River via a tax credit (HR388).* The tax credit was set at $1,000 per acre foot of treated water (about $0.13/barrel), not to exceed $400,000 per year per company. The legislature acted on this issue namely because the Pecos watershed was strongly impacted by drought in the preceding years, and additional recharge to the river was intended to support delivery of water downstream to Texas to meet water compact obligations. A consortium of water authorities in Lea and Eddy counties in southeastern New Mexico paid for studies that examined the costs, infrastructure needs, and feasibility of treating and discharging produced water.** No discharges ever occurred (likely due to the cost of treatment as compared to the credit), and the legislation has expired; however the reports remain a useful and detailed assessment of the legal, technological, and economic requirements for enabling discharge of produced water in 2004 in New Mexico.

* HR388, https://www.nmlegis.gov/Sessions/02%20Regular/FinalVersions/house/H0388.pdf (2002).

** NRCE, Inc., *Water in the Desert: Engineering/Legal/Logistical Study to Implement the Conversion of Oil and Gas Produced Water to Useable Water in Lea and Eddy Counties, New Mexico*, "Executive Summary," (January 2004); M. F. McGovern and E. E. Smith, *Delivery of Treated Produced Water from Indian Basin and Dagger Draw to the Pecos River, Eddy County, New Mexico: Concept Report and Cost Analysis*, R.T. Hicks, Consultants, Ltd., (2003).

Research and Evaluation of Reuse Options: A Decision-Making Framework

Any expansion of produced water reuse or discharge outside oil and gas operations will come with a host of questions from a variety of stakeholders. These stakeholders and decision-makers range from regulators and operators to environmental groups as well as the potential end-users of treated produced water. A common question will be, "What are the benefits and risks?"

There has been rapid growth in both research and technology development aimed at characterizing and treating produced water – initially for the purpose of reuse within oil and gas operations. As attention turns toward more in-depth assessment of the potential for other alternatives, the scope of considerations expands significantly to include new, complex issues ranging from liability to potential ecological and health hazards.

As the National Research Council has noted, the "pursuit of the best scientific understanding is inevitably resource-intensive and time-intensive, and this leads to conflict with other objectives and with constraints on resources."[159] This fact underscored why a framework is needed to identify critical questions to support smart decisions, recognizing these potential conflicts while aiming to maximize potential benefits and reduce impacts to health and the environment.

Evidence-based risk assessment serves as a vital component for informed decision-making. While the desire to use treated produced water for various purposes in lieu of disposal is understandable, the regulations or guidelines currently in place to ensure that the range of potential uses can be safely achieved may be limited. Decision-makers who have the responsibility for protecting people and the environment, need to weigh potential benefits and risks. The decision-making and risk assessment process should be based on the understanding that produced water from oil and gas operations is a complex mixture with a composition that may be difficult to precisely characterize, though adequate fit-for-purpose characterization should ultimately be achievable. Sufficient understanding of constituents of concern prior to treatment will be required to design appropriate treatment

159 National Research Council, *Science and Decisions: Advancing Risk Assessment,* (Washington, DC: The National Academies Press, 2009), p. 68, https://doi.org/10.17226/12209.

Who Are the 'Decision Makers'? A number of stakeholders may be involved or should be considered in evaluating new management practices for produced water. Some of these may not be obvious "decision makers," but their unique perception of the issues and influence on a path forward may be significant. Each stakeholder is likely to bring a different set of concerns and considerations to the table at different stages, and there will be different types of decisions to be made.

These stakeholders may include:

- **Operators**, who will determine whether costs and risks favor a new water management strategy
- **Regulators and legislators**, who will determine whether and how to permit and monitor new practices
- **New end users**, who will seek sufficient reliability, quality, and comfort to use a new water source
- **Communities and municipalities**, whose residents will have specific local considerations
- **Special interests**, whose members will be focused on endangered species, wildlife habitat, recreation, watershed, and groundwater protection
- **Property and mineral owners**, whose interests may be impacted
- **General public**, who will have questions about safety, health, and unknowns.

systems and assess the efficacy of the treatment, as well as identify and define potential constituents of concern for monitoring and limitation in specific discharge or reuse scenarios. Basing an assessment only on well-known constituents of concern or by using standards that exist today for other purposes may not be sufficient. Reuse for a specific non-industrial purpose should be based on evidence showing that the actual receptors of interest (human, agricultural, ecological, and terrestrial) will not be exposed to hazards in such a way as to cause harm. As such, defining the appropriate standards for assessment and risk management will require investigation and research.

The need for water should not justify bypassing a risk assessment process. Movement toward new reuse options will likely be supported more quickly and broadly where decision-makers and risk assessors provide consistent, transparent, and scientifically robust assessments, and openly engage and communicate with stakeholders regarding their plans and findings.

This section brings together what is known and unknown to better represent the holistic challenge at hand and a potential path forward. What do stakeholders need to know about produced water to make informed decisions about its treatment and use in potential reuse scenarios? What can be done to better identify and reduce risks to the environment and human health? What other important trade-offs or considerations must be addressed for reuse proposals to move forward? Overall, how do we assess and manage potential and perceived risks?

Science and Risk-Based Decision Making: General

The incorporation of risk into decision making for the permitting of new practices is not unique to the assessment of treated produced water reuse. In fact, numerous books, guidelines, rules, and policies have been written promoting the use of risk-based science in decision-making. As research and collaborative efforts progress to investigate opportunities to reuse treated produced water, past experience and available materials should be referenced and leveraged, if applicable.

One example resource is the book *Science and Decisions: Advancing Risk Assessment*, published by the National Research Council (NRC). The NRC provides a substantive discussion of the fundamentals involved in assessing risk and utilizing research and information to support decisions.[160] The book includes a variety of iterations on the process, including the general framework shown in Figure 3-8:

160 *Ibid.*

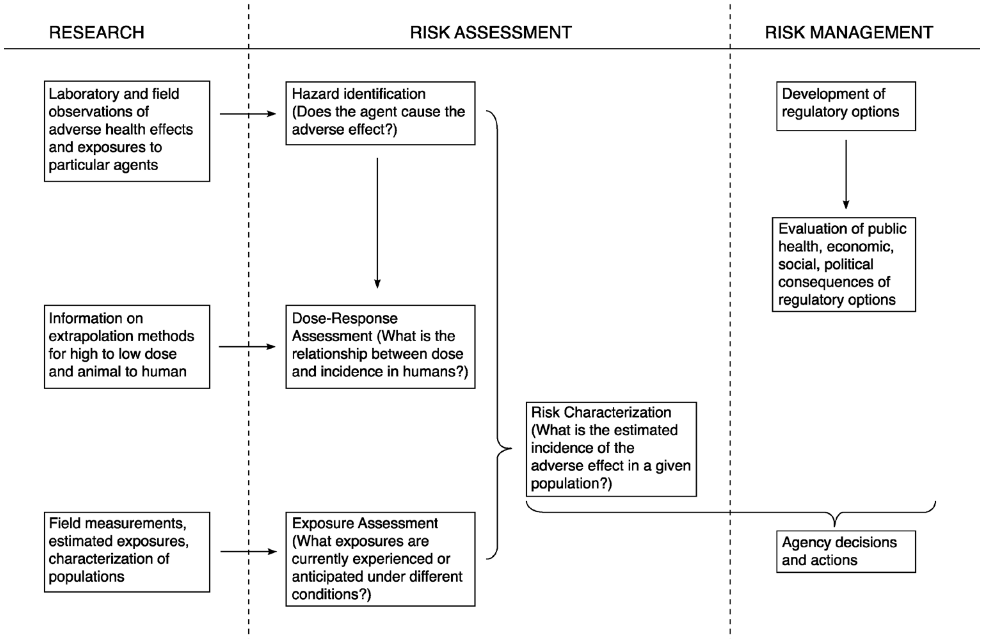


Figure 3-8: National Research Council Risk-Assessment-Risk-Management Paradigm

Source: National Research Council, Science and Decisions: Advancing Risk Assessment (p. 31), Figure 2-1 (2009)

The NRC also makes salient points about the process and benefits of risk assessment. Some important concepts discussed are the benefits of and value obtained from the risk assessment process. NRC notes:

"Given the demands of health and environmental decision-making, perhaps the most appropriate element of quality in risk-assessment products is captured in their ability to improve the capacity of decision-makers to make informed decisions in the presence of substantial, inevitable and irreducible uncertainty. A secondary but surely important quality is the ability of the assessment products to improve other stakeholders' understanding and to foster and support the broader public interests in the quality of the decision-making process (for example, fairness, transparency, and efficiency). Those attributes are difficult to measure, and some elements of quality often cannot be judged until sometime after the completion of the risk assessment."[161]

Other groups have developed guidelines and documents related specifically to water and wastewater reuse. In a 2018 webinar on water reuse, EPA experts from the Office of Research and Development (ORD) National Exposure Research Lab reviewed key considerations by EPA and others. The ORD presented the challenge of finding new water resources with three seemingly simple questions:

(1) how to define the acceptable treatment,

(2) how to monitor treatment effectiveness, and

(3) does it make sense to do this?[162]

These questions present a useful parallel to the evaluation of produced water treatment and reuse.

> **COMMUNICATING RISK**
>
> A key learning from other reuse scenarios is the need to manage the conversation regarding risk — a concept that is not unfamiliar for oil and gas operators and regulators. Risk communication must be transparent and focus on educating the public about actual risk in order to avoid fear or assumptions of unrealistic impacts. Data, transparency, communication, and expanded opportunities for information sharing can help to prevent misperceptions.

Expanding reuse practices can take time and resources. Research consortiums, multi-stakeholder groups, and other organizations are working to

161 *Ibid.* p. 67.

162 USEPA Tools and Resources Webinar on Non-potable Water Reuse (Oct. 17, 2018).

understand and work toward implementation of reuse scenarios for other waters. The US Water Alliance partnered with the Water Research Foundation to establish the National Blue Ribbon Commission for Onsite Non-potable Water Systems to look for innovative solutions, allow for knowledge exchange, develop guidance and frameworks, identify research needs, and develop resources[163] for onsite non-potable water systems that could be used to recycle graywater, stormwater, rainwater, etc. from buildings or other sources to replace freshwater use for things like toilet flushing, cooling, or irrigation. The Water Environment & Reuse Foundation recognized the lack of national standards or guidelines for these types of systems and developed a report that included a risk-based framework for the development of public health guidance for decentralized non-potable water systems.[164] Similarly, the World Health Organization has developed guidelines on wastewater reuse in certain contexts.[165] These documents describe varying approaches to assess risk, establish protective standards and best practices, advance monitoring tools, and make smart decisions that support reuse while protecting health and the environment given a range of challenges from data limitations and uncertainty to public perception.

States often conduct research and assess risk to support new programs and evaluate whether existing standards are appropriate or new standards may be necessary. For example, when Oklahoma considered Indirect Potable Reuse of domestic wastewater, the Oklahoma Water Resources Board and Oklahoma Department of Environmental Quality worked together, along with a stakeholder group including the regulated community, technical experts and the general public, to develop the new program, recognizing early in the process that the existing standards and implementation for typical point source discharges would not be adequate for the unique circumstances. After research and technical consideration, the agencies developed a program that included advanced effluent benchmarks, modeling of effluent impact to evaluate multiple factors, additional operation and maintenance requirements, and receiving water body monitoring and trend analyses. The program also involves quarterly monitoring of constituents on a list of Constituents of Emerging Concern (CEC) that requires corrective action if levels are exceeded, while also collecting data that informs the development of a more representative list of CEC's and ongoing efforts to set risk-based screening and action levels.[166] This process took about six years, with a working group convening in 2012 and new Indirect Potable Reuse rules adopted in 2018.

Water and wastewater reuse of any kind, if done incorrectly, can result in significant repercussions. Negative impacts obviously include contamination or health effects, but another risk is reluctance to try reuse again in the future. Therefore, it is vital that reuse options proceed in an informed and cautious way, particularly in early stages.

The Framework

The following is a general framework for the evaluation of reuse options, focusing primarily on research needs. At its foundation, the framework relies on traditional risk-assessment principles but is both modified and expanded to better address the unique challenges of produced water and recognize a broader range of important considerations. Each section is discussed in detail below the framework overview.

> Assessments conducted with currently available information should recognize, where appropriate, that unknowns and uncertainties exist, and decisions should be revisited for improvements where new information, technologies, and data become available.

The framework is designed to assist decision-makers in working through analysis of a given reuse scenario, providing guidance regarding the type of questions and steps that may inform assessment of a given project. It is intended to spur discussion and

163 National Blue Ribbon Commission for Onsite Non-potable Water Systems, US Water Alliance, http://uswateralliance.org/initiatives/commission.

164 Water Environment & Reuse Foundation, *Final Report: Risk-Based Framework for the Development of Public Health Guidance for Decentralized Non-Potable Water Systems* (2017).

165 See e.g., World Health Organization, *Guidelines for the Safe Use of Wastewater, Excreta and Greywater – Volume 2, Wastewater use in agriculture* (2006), http://www.who.int/water_sanitation_health/wastewater/wwuvol2intro.pdf.

166 Email correspondence with Oklahoma Department of Environmental Quality. See also Oklahoma DEQ Indirect Potable Reuse Rules, OAC 252:628-1-3 (adopted in 2018).

help to focus research and development efforts in a way that support decision-making on reuse in the future. While this framework seeks to serve as a useful guide in assessing a specific reuse scenario, GWPC does not intend to prescribe a single set process for assessing individual reuse proposals. Instead, GWPC expects this effort to encourage collaboration, targeted research, and further engagement surrounding this important issue, including refinement of this framework.

At present, existing data gaps in chemical and toxicological characterization of produced water present limitations for implementation of this framework for specific reuse scenarios – namely, the identification of potential constituents of concern for analysis, treatment, and monitoring. Efforts to broaden this knowledge through advancements in analytical and toxicity testing tools are ongoing and may allow for more comprehensive assessment in the future. Advancements may be furthered by pairing characterization efforts with treatment studies or pilots, where some barriers to study can be lessened through targeted treatment. Moving forward, this conceptual framework and research conducted in furtherance of this framework should be revisited as data gaps are filled by chemical disclosures, new analytical methods, treatment systems, toxicological information and the like.

The framework consists of four key phases:

- **Phase I: Preliminary review of the proposed program.** The goal of this phase is to define the scope of the proposed program and conduct an initial, cursory assessment to determine whether the reuse scenario is likely to be feasible and if additional analysis is worth investment. This may include a screening-level assessment of the known, basic chemistry of the produced water as compared to the known, basic quality needs or objectives for the end use, as well as an initial evaluation of expected treatment needs. This phase should also incorporate an initial assessment of non-research considerations such as economics, logistics, infrastructure, and public perception. Stakeholder involvement may be incorporated to better identify and address these.
- **Phase II: Identification of stressors of interest for treatment and risk analysis.** This phase is devoted to adequately characterizing the produced water and decision-making regarding appropriate treatment technologies. Characterization of both influent and treatment effluent is necessary in order to identify the "stressors" or chemicals and other constituents of interest that should be targeted for removal and further analyzed in the risk assessment phase. This phase includes both characterization and treatment technology assessment and may also incorporate research objectives on both analytical method development and treatment technology advancements and testing. The end result of this phase aims to help narrow the scope of further consideration to characterization of expected effluent and priority constituents of concern for consideration in a scenario-specific risk assessment.
- **Phase III: Risk assessment (applied to treated produced water).** Phase III focuses on a traditional risk assessment, based on models of analysis commonly employed by risk assessors and agencies. This includes hazard identification, dose-response assessment, exposure assessment, and risk characterization — all based on the proposed reuse program and expected stressor(s). While this framework focuses on the fluid itself, similar risk assessment process could be necessary for solids and other residuals from treatment, though this framework focuses on the fluid itself.
- **Phase IV: Risk management and decision making.** Phase IV aims to support an informed decision to move forward with a project and define the necessary risk management strategies. It includes a final evaluation of the considerations of Phase I, a decision on whether the risks as characterized are manageable, and an effort to implement or develop the appropriate risk management strategies, including quality standards and permit limitations, monitoring tools, best practices, and information sharing. Phase IV also recognize the importance of a process of continuous learning and incorporation of new knowledge or tools.

RISK ASSESSMENT TERMINOLOGY

- **Risk assessment:** EPA notes that risk assessment is, to the highest extent possible, a scientific process. In general terms, risk depends on three key factors: (1) how much of a chemical is present; (2) how much contact (exposure) a person or ecological receptor has; and (3) the inherent toxicity of the chemical. Risk assessments traditionally focus on individual chemicals, though assessment of complex mixtures is an increasing area of investigation.
- **Stressor:** Any physical, chemical, or biological entity that can induce an adverse response. In the context of produced water, this might be a constituent of concern or the mixture itself. Stressors may adversely affect humans, specific natural resources, entire ecosystems, or other ecological receptors.
- **Dose-Response:** Examines the relationship between an exposure and effects.
- **Exposure Assessment:** Examines what is known about the frequency, timing, and levels of contact with a stressor.
- **Hazard Identification:** Examines whether a stressor has the potential to cause harm to humans and/or ecological systems, and if so, under what circumstances.
- **Variability:** Toxic response or exposure depending upon numerous factors. Variability must be considered in risk assessment.
- **Uncertainty:** Incomplete data often means that assessors are incapable of knowing "for sure" what the risks are to people and environments. Uncertainty must be factored into account.

From USEPA, "About Risk Assessment," https://www.epa.gov/risk/about-risk-assessment and USEPA's "Risk Assessment Glossary."

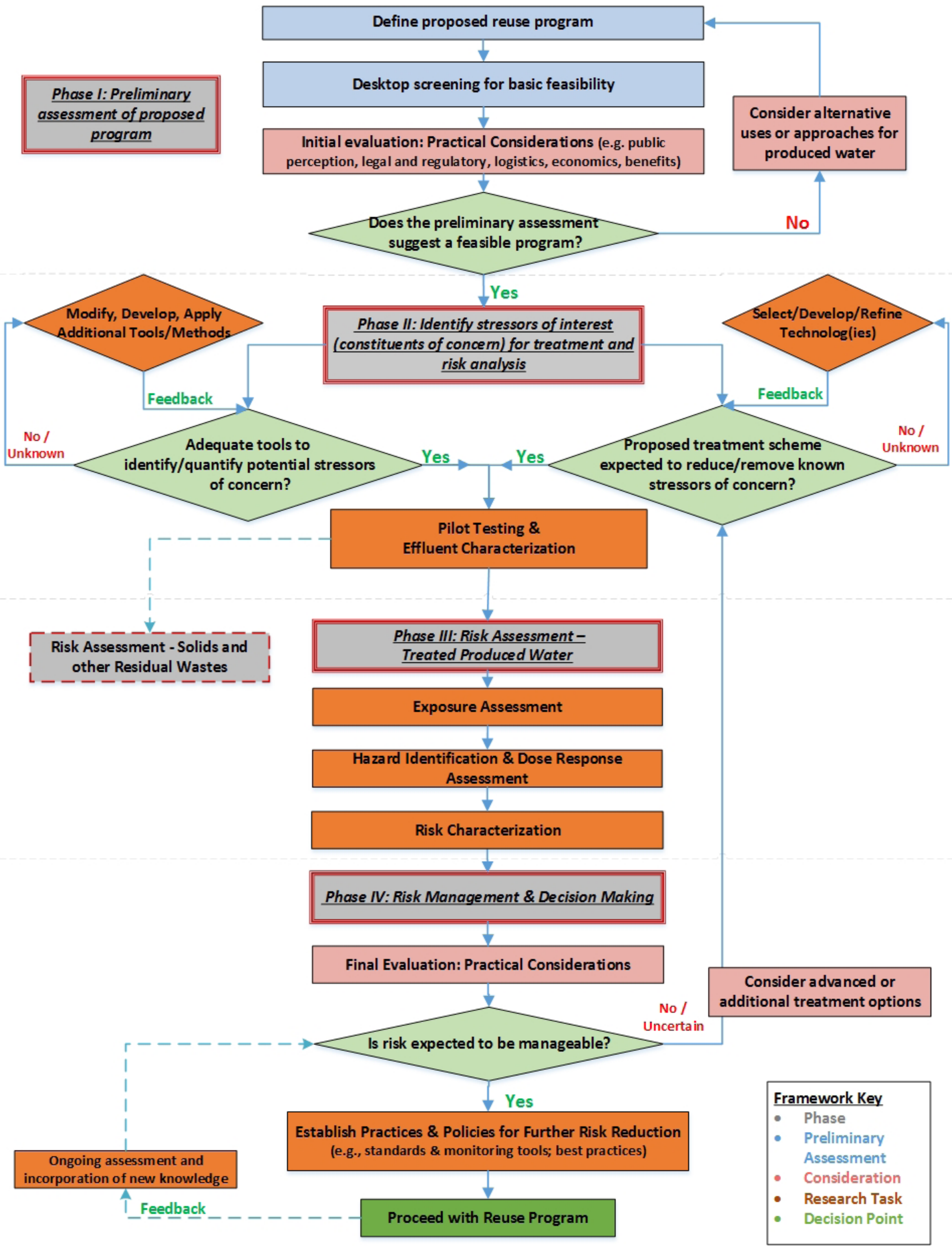
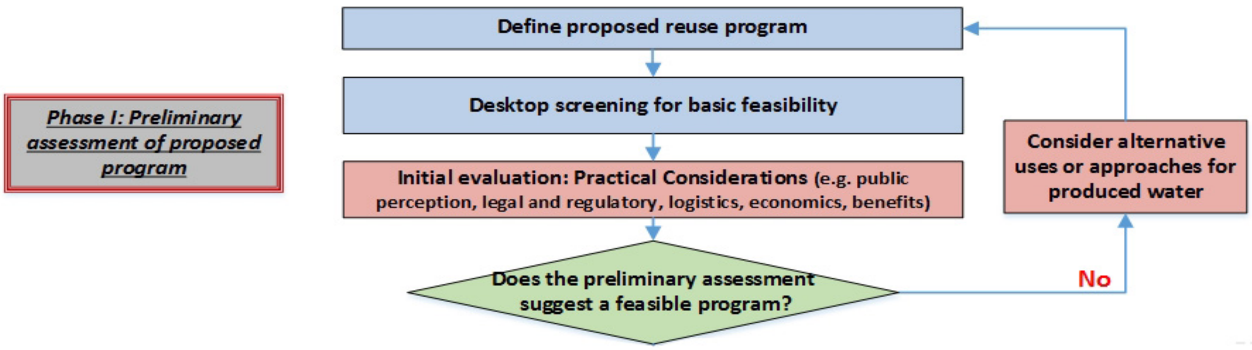


Figure 3-9: Framework for Research, Evaluation and Decision-Making

Phase I: Preliminary assessment of proposed program



Phase 1 Overview and Goals: The preliminary screening and assessment predicts the viability and value of a proposed reuse program. A feasibility evaluation using existing data is intended to avoid unnecessary investment of time and resources. In cases where this preliminary evaluation indicates that a reuse option may indeed be feasible, the effort expended in Phase I allows data gaps and required research to support subsequent risk characterization to be identified and scoped.

Each step of the Phase I Preliminary Assessment is detailed below.

Define proposed reuse program

Step one in this decision framework includes definition of key facts and information, such as:

- Proposed category of use: e.g., industrial, municipal, agricultural, ecological, etc.
- Identification of project drivers and expected benefits/beneficiaries
- Water volumes potentially available and needed
- Expected variability in produced water quality, quantity, availability
- Timeline and duration of project; case-specific demand considerations such as seasonality, etc.
- Location description and characterization, including potential receptors and exposure pathways
- Proposed method of delivery for reuse (e.g., discharge, pipeline, aquifer recharge)
- Available treatment technologies and projected effluent quality
- Option for management of treated water and waste streams, including solids

Desktop screening for basic feasibility

The goal is to gather readily available or obtainable information to better define known, basic water quality needs for the proposed use for comparison to the produced water that may be available or utilized. This screening step will not necessitate a thorough characterization of receptors or substantive chemical analysis of produced water. Instead, the benefit will be a basic representation of the scale of the challenge ahead. In some cases, a preliminary screening may indicate that a project is simply not currently feasible or economic. In other cases, a preliminary screening may show good promise for a potential project and support investment in further investigation.

Accelerating progress with collaboration. Identifying producing companies and research partners willing to come together to share water, characterization, treatment, and piloting data and resources would accelerate the progress of produced water treatment and reuse.

One example is the Marcellus Shale Energy and Environment Laboratory (MSEEL), where government and academic researchers work together with industry on a long-term field site to study unconventional oil and gas development. (www.mseel.org).

The desktop analysis may involve three basic parts:

1. *Gather available guidance, standards, requirements, etc. on known water quality needs/goals for the proposed use. The scope of this step will vary based on the intended end use.* The expectation is not that the available guidance or standards will address all constituents of concern or relevance in produced water. Instead, the goal is a basic understanding of the estimated water quality objectives. Sources of information might include national water quality criteria, published literature, guidelines for water reuse, published irrigation criteria, etc.[167]
2. *Conduct a screening level analysis of the produced water that may be considered for a treatment and reuse program.* This step will involve analysis of known produced water constituents that are likely to be relevant to an assessment of feasibility utilizing existing, approved analytical methods. It may be possible to use existing knowledge and data or reports available on the produced water to limit this step to a desktop study. Additional resources may include MSDS data sheets and known additives utilized in operations as well as the website for hydraulic fracturing chemical disclosure, FracFocus.org. Parameters may include:
   - Basic water quality: TDS, TSS, BOD, pH, alkalinity
   - Inorganics/metals: NH3, H2S, PO4, Pb, Fe, Zn
   - Organics: TOC, TPH, BTEX, PAH, VOC, SVOC
   - Radionuclides
   - Other constituents expected to be present, based on generator knowledge and/or those common to produced water, that may pose a challenge to meeting water quality needs – for example, biocides or methanol in cold-weather locations.
3. *Preliminary assessment, treatability, and comparison to known water quality goals.* Based on available information on water quality objectives and chemical character of produced water, this step seeks to develop a basic understanding of the challenge. For example, is it economically feasible to reduce TDS to levels identified utilizing available technologies? Consider available treatment technologies needed to achieve known treatment goals and management of waste streams.

Initial evaluation of practical considerations

Any decision on produced water reuse will entail practical considerations beyond those addressed explicitly in this framework. Such considerations may hold an equal or greater influence on decisions when compared to ecological or health risk concerns and, alone or collectively, can be a deciding factor for an alternative use proposal. See pages 154–161 for a more substantive overview of these considerations, which include law and regulation, public perception, logistics, economics, environment, and benefits.

Decision: Does the preliminary assessment suggest a feasible program?

This decision point presents an opportunity to determine if analysis conducted up until this point supports a decision to move forward with a more substantive risk characterization process or better supports the consideration of an alternative approach. Ideally, minimal effort and money have been invested in a preliminary "go/no go" decision.

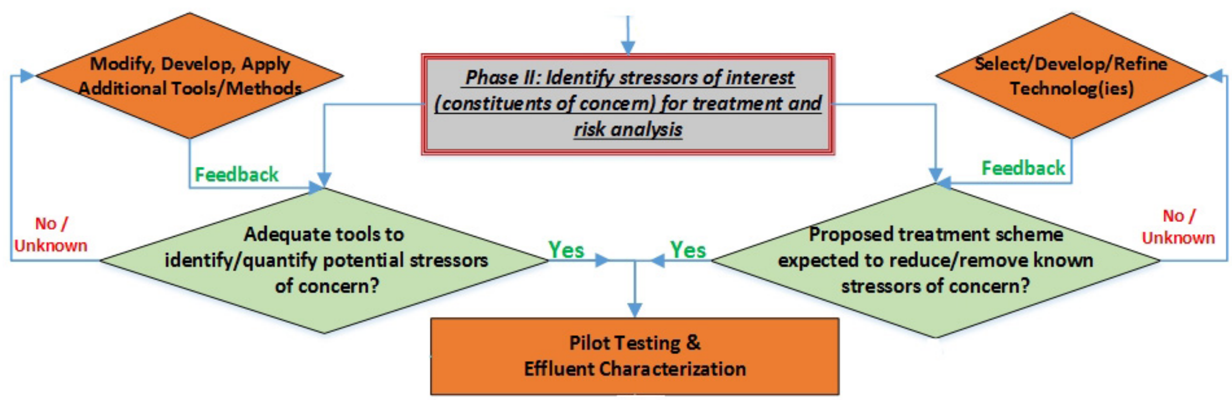
"No" a finding that the project is not expected to be currently feasible based on a screening assessment, will lead to a consideration for alternative approaches. Such alternatives may include utilization of existing disposal methods, or alternative strategies that may lead to a use scenario after preliminary assessment and results in a "yes" decision to move forward.

167 A broader list of example resources might include: state and federal water quality criteria for protection of aquatic life, human health, drinking water standards, etc.; USEPA Guidelines for water reuse, https://www3.epa.gov/region1/npdes/merrimackstation/pdfs/ar/AR-1530.pdf; published literature that provides a sound technical basis for establishing quality objectives for specific stressors of interest, e.g., R.S. Ayers and D.W. Westcot, *Water Quality for Agriculture, Irrigation, and Drainage*, Paper 29, Rev. 1, Food and Agriculture Organization (1994); G. Fipps, *Irrigation Water Quality Standards and Salinity Management Strategies*, Texas Cooperative Extension B-1667 (April 2003) 19; K. Guerra, K. Dahm, and S. Dundorf, *Oil and Gas Produced Water Management and Beneficial Use in the Western United States*, Bureau of Reclamation Science and Technology Report No. 157, 113 (2011); and American Petroleum Institute, *Risk-Based Screening Levels for the Protection of Livestock Exposed to Petroleum Hydrocarbons* (2004).

"Yes" a finding that the project may be feasible based on a screening assessment, will lead the decision-maker into a more substantive data collection and risk assessment phase.

Regulatory consideration: early engagement with state and/or federal agencies that may have jurisdiction can help gain acceptance, reduce time delays, and provide insight into additional considerations that need to be assessed in judging project viability and feasibility.

Phase II: Identify stressors of interest (constituents of concern) for risk assessment



Phase II Overview and Goals: Better understanding the quality of produced water, including its chemical constituents, is a key need for both risk assessment and designing and testing appropriate treatment options.

This phase connects a more in-depth analysis of the produced water quality proposed for reuse with research and development or identification of a fit-for-purpose treatment train, potentially including pilot testing. As much clarity, where feasible, on the constituents present in untreated produced water is useful to assess treatment efficacies and will inform which constituents should be prioritized for permitting or monitoring purposes. Phase II does not intend to imply that exhaustive characterization of produced water is a necessary requirement to move to Phase III. Instead, this phase aims to emphasize that partnering advancements in characterization with treatment technology design and assessment allows for a more informed risk assessment and management phase. This allows for the targeting of specific constituents of concern for removal, but also allows for an improved understanding of the chemicals or classes of chemicals that may be expected in liquid effluents or in solids or residuals. Importantly, initial characterization of produced water in the context of a fit-for-purpose reuse project affords an opportunity to create a more effective, robust, and protective treatment and monitoring program.

This phase represents the realities of an iterative assessment process. For example, there may be ongoing analysis necessary to identify potential stressors of concern, particularly if new or modified analytical methods are deemed necessary or become available. This means that new information may feed into the analysis in an ongoing manner, and potentially inform treatment technology design and assessment as well as effluent characteristics. The same may be true for treatment technologies, as new options are developed and tested to address various stressors or reach quality goals. Overall, it is not expected that there will be a "final" answer at this stage, but rather a recognition of what is known and unknown, and a commitment to iterative incorporation of new data or technologies as they are developed. This process allows for continuous learning and advancement that can create more efficient and protective treatment and reuse programs. The acknowledgement of the need for such iteration, however, does not necessarily mean that a potential project should not be further analyzed or pursued given tools and knowledge available today. Finding a balance between supporting the advancement of produced water reuse projects while recognizing opportunities for knowledge and process improvement will be a key challenge.

Decision: Adequate tools to identify/quantify potential stressors of concern?

The aim of this decision point is to determine whether the appropriate methods exist to identify potential stressors of concern at appropriate quantification levels in the produced water for its proposed reuse. Potential stressors in produced water can be grossly broken down into general water chemistry parameters (pH, total dissolved solids, temperature, etc.), inorganic constituents (ions and metals), radionuclides, and organic chemicals. The availability of methods to quantify these four classes of constituents vary, particularly for organic constituents, which are not well characterized in produced waters.[168] While existing methodologies are likely to exist that can greatly inform the characterization effort, there may be a need for expanded research to modify or develop new methods. Challenges associated with accuracy, interference, and other limitations associated with raw produced water are lessened significantly in treated water, but the challenges associated with a lack of methods for some constituents of concern applies regardless of the level of treatment. A key objective is ensuring that the right constituents are being removed to protective levels, and this involves an improved understanding of treatment targets. In all cases, advancing our ability to characterize the constituents of concern in produced water better equips researchers, technology developers, operators, and regulators alike with the tools and information necessary to design and assess treatment methods, carefully select indicator compounds for monitoring, or establish the appropriate limits for constituents of concern as treated produced water is considered for a new reuse option.

Existing methods can be generally described as follows:

- **General water chemistry analytical methods** include pH, total dissolved solids, alkalinity, hardness, and others that are routinely measured in water, wastewater, and produced water. These methods are established and frequently used in produced water analysis. However, interferences still exist for several of these analyses as applied to produced water. For example, turbidity interferes in USEPA Method 310.2, which measures alkalinity. As such, considerations should be taken for each method and the complexity of produced water being characterized.
- **Inorganic constituents (ions and metals) and radionuclides**, have established methods that can be used for produced waters. For example, USEPA methods 300.0 (major anions), 200.7 (metals), 901.1 (gamma emitters), and 9310 (gross alpha/beta) are certified methods that are routinely used for regulated constituents in water and wastewater (e.g., those that have Minimum Contaminant Levels [MCL]). However, the complex matrix of produced water can present challenges for these methods that were developed for fresh water. In particular, EPA method 903.0, which effectively measures isotopic radium levels in fresh water, has been demonstrated by one study to be inaccurate when applied to produced waters.[169]
- **Some established methods for organic constituents** can be applied to produced water. For example, USEPA methods 8260 (volatile organic compounds) and 8270 (semi-volatile organic compounds) as well as USEPA methods 624 and 625 for the same constituents are

168 Jenna L. Luek and Michael Gonsior, "Organic Compounds in Hydraulic Fracturing Fluids and Wastewaters: A Review." *Water Research* 123 (October 2017), 536–48, https://doi.org/10.1016/j.watres.2017.07.012; Karl Oetjen, Cloelle G.S. Giddings, Molly McLaughlin, Marika Nell, Jens Blotevogel, Damian E. Helbling, Dan Mueller, and Christopher P. Higgins, "Emerging Analytical Methods for the Characterization and Quantification of Organic Contaminants in Flowback and Produced Water," *Trends in Environmental Analytical Chemistry* 15 (July 2017) 12–23, https://doi.org/10.1016/j.teac.2017.07.002.

169 Andrew W. Nelson, Dustin May, Andrew W. Knight, Eric S. Eitrheim, Marinea Mehrhoff, Robert Shannon, Robert Litman, and Michael K. Schultz, "Matrix Complications in the Determination of Radium Levels in Hydraulic Fracturing Flowback Water from Marcellus Shale," *Environmental Science & Technology Letters* 1 (3):204–8 (2014), https://doi.org/10.1021/ez5000379.

certified methods routinely used for regulated constituents in water and wastewater, which are also stressors found in produced water. These methods could capture some important volatile and semi-volatile compounds in produced water; however, the organic chemical makeup of produced waters is complex and poorly understood. This is due to the fact that produced waters potentially contain a mixture of fracturing fluid chemicals, geogenic compounds from the formation, and unknown reaction products that can be formed in the subsurface. While these methods are validated and appropriate for fresh or treated waters, their application to untreated produced water will likely require modified sample preparation to account for challenges such as matrix interference from dissolved solids like salt.

Waters can contain total organic carbon (TOC) levels greater than 1500 mg/L (Rosenblum),[170] with little of this TOC characterized given the lack of validated methods for quantification.[171] As such, a likely research need is better determining the nature, toxicity and treatability of TOC.[172]

Research Task: Modify, develop, apply additional tools/methods

The goal of this task is to develop appropriate analytical methods or tools to more thoroughly identify and quantify stressors. This research task aims to address any analytical limitations that have been identified in the decision point above and provide feedback that results in more informed decision-making on stressor identification. The focus of this research objective would include defining the path towards identifying potential stressors using analytical tools or bioanalytical tools (e.g., bioassays) that can quantify known or unknown stressors. This work may take into consideration learnings from existing or ongoing studies on this topic (see "State of the Science: Literature Review").

Effectively applying existing methods and potentially developing new analytical tools for stressor identification is a critical step in understanding produced waters and their constituents. Robust chemical characterization begins with proper sample collection and ends with validating methods that are able to accurately quantify stressors in produced water. As previously highlighted, while many of the standard methods for waters and wastewaters that are available can be applied to produced water analysis, interferences can pose unique challenges for reliable characterization. Thus, alternative methods are needed, or procedures outlined on how to manage these interferences (i.e. clean-up or dilution) to accurately measure constituents. In addition, some potential constituents of concern that have been identified in produced water lack approved analytical methods. As a result, there may be a need to develop and gain approval of methods for constituents identified as a priority.

In one study, Oetjen et al. developed a table (Appendix 3-C) of suggested analytical methods for analyzing target analytes, based on chemical groups or types, which are likely present in produced water.[173] Researchers developed a table that listed available methods (either research or standardized) and included any pre-treatment requirements that might be necessary. However, the research team notes that quantification of analytes in produced water will be challenging; furthermore, a combined effort of non-targeted screening to identify unknown constituents will need to be coupled with targeted analysis and method development.

Examples of research include:

- **Standard methods development and validation.** There is a demonstrated need to develop standard sampling procedures for produced water, followed by analytical method validation

170 James Rosenblum, E. Michael Thurman, Imma Ferrer, George Aiken, and Karl G. Linden, "Organic Chemical Characterization and Mass Balance of a Hydraulically Fractured Well: From Fracturing Fluid to Produced Water over 405 Days," *Environmental Science & Technology* 51 (23):14006–15 (2017), https://doi.org/10.1021/acs.est.7b03362.

171 Marika Nell and Damian E. Helbling, "Exploring Matrix Effects and Quantifying Organic Additives in Hydraulic Fracturing Associated Fluids Using Liquid Chromatography Electrospray Ionization Mass Spectrometry," *Environmental Science: Processes & Impacts* (2018), https://doi.org/10.1039/C8EM00135A.

172 For additional discussion of dissolved organics, see John M.Walsh, James Vanjo-Carnell and Jarid Hugonin, "Understanding Water Soluble Organics in Upstream Production Systems," SPE-170806-MS, (2014).

173 Karl Oetjen, Cloelle G.S. Giddings, Molly McLaughlin, Marika Nell, Jens Blotevogel, Damian E. Helbling, Dan Mueller, and Christopher P. Higgins, "Emerging Analytical Methods for the Characterization and Quantification of Organic Contaminants in Flowback and Produced Water," *Trends in Environmental Analytical Chemistry* 15 (July 2017) 12–23, https://doi.org/10.1016/j.teac.2017.07.002.

to create standard procedures that will ensure uniform chemical characterization from lab-to-lab. This is likely to include a need for research or reference materials to validate findings and results.[174] Method validation can be a lengthy process that requires inter-lab coordination to assure method performance meets a particular need as applied (i.e., measuring constituents at relevant concentrations).[175] Given the time and cost associated with method development and validation, and the many potential constituents present in produced water, prioritization is challenging. Therefore, one area for initial effort is the identification of chemicals that should be prioritized for method development based on data points such as known hazards, identified presence in produced water, and expected concentrations.

- **Sample preparation and matrix interference analysis.** Numerous analyses require sample clean-up due to the complex nature of produced water and assessment is needed to confirm best practices. A common method used by analytical chemists to manage matrix interference is to simply dilute samples prior to analysis; however, for trace elements or constituents of concern that are harmful at low concentrations, this practice may detrimentally affect analytical accuracy by raising detection limits.[176] Such assessments will validate extraction and clean-up procedures, identify key inhibitors (e.g., chloride) that can impact analysis, and demonstrate best practices on how to remove them.

- **Identification of treatment-resistant unknowns.** Potential knowledge limitations on constituents of concern that are in produced water influent streams or how those chemicals may be transformed during treatment in specific scenarios may make measuring treatment efficiency challenging. Therefore, there may be a need to identify unknowns in treatment effluents using non-targeted analytical techniques including high-resolution mass spectrometry (HRMS). It should be noted that HRMS, while able to provide valuable insight into chemical characteristics of a sample, can be time- and resource-intensive. Therefore, HRMS should be viewed as a valuable tool for research and development to identify potential constituents of concern in untreated

Sample collection for produced waters can present challenges for water analysis. This is due to potential variation in water quality based on sample location (i.e., well-head, separator, or tank battery) or impacts to the sample due to the manner in which the samples are handled and preserved. If the produced water remains in tank batteries for extended periods of time, organic chemicals may degrade. If, however, the sample is collected at the well-head, prior to separation, it may contain both oil and water.

Establishing how, where, and even when to sample is an important consideration for produced water analysis to ensure consistent analysis occurs from study to study and accurate information is available to inform treatment. Additionally, standard water analysis methods can be impacted by constituents in produced water that can either suppress or interfere with the analyte of interest. How fluid is collected and managed and where in a process to collect produced water for analysis and treatment are critical considerations. Overall, the validation of numerous standard methods, how best to deal with interferences, and how to assure the collection of useful data should be considered an important research area, to ensure standard procedures are done from lab-to-lab.

174 See, e.g., S. Christopher, D. Bearden, C. Davis, and K. Huncik, "Development and chemical characterization of a hydraulic fracturing wastewater reference material," presented in *Comprehensive Chemical Characterization of Hydraulic Fracturing Shales, Wastes & Recycled Waste Products,* symposium conducted at the 255th National Meeting of the American Chemical Society, New Orleans, LA, March 2018.

175 See, e.g., USEPA, Protocol for Review and Validation of New Methods for Regulated Organic and Inorganic Analytes in Wastewater Under EPA's Alternate Test Procedure Program, 2016, https://www.epa.gov/sites/production/files/2016-03/documents/chemical-new-method-protocol_feb-2016.pdf.

176 T.L. Tasker, W.D. Burgos, M.A. Ajemigbitse, N.E. Lauer, A.V. Gusa, M. Kuatbek, D. May, et al., "Accuracy of Methods for Reporting Inorganic Element Concentrations and Radioactivity in Oil and Gas Wastewaters from the Appalachian Basin, U.S. Based on an Inter-Laboratory Comparison," E*nvironmental Science: Processes & Impacts*, (2019), https://doi.org/10.1039/C8EM00359A.

produced water and to confirm removal during and after treatment technologies as they are tested and piloted. Subsequent monitoring and treatment assessment can be performed using less-demanding analytical techniques for priority constituents of concern found above de minumus concentrations that are likely to be treatment-resistant, are identified as being harmful at low concentrations, or on their carefully selected indicator compounds, as long as appropriate methods exist or are developed. Furthermore, while this approach can help identify unknown constituents this method does not address the collective risk posed by the combined known and unknown contaminants identified. Thus, a practical solution is to integrate whole effluent toxicity (e.g., WET assessment) or other bioanalytical tools. This is a common strategy applied in practice to other wastewater streams, such as municipal effluents, for quantifying potential effects of multiple stressors.

- **Validation of toxicity bioassays.** Outside initial characterization studies or research applications, comprehensive, in-depth chemical characterization of produced water is often cost-prohibitive and may be unnecessary. However, it will be necessary to have a reliable assessment of the potential toxicity of the treated produced water proposed for reuse or discharge. Therefore, toxicity screening bioassays, which may quantify or predict the effect of both known and unknown stressors in the mixture itself, are a logical compliment to chemical characterization methods. For surface water discharges, a variety of standard WET methods are available.[177] In the case of other reuse scenarios, such as those where land application is considered, new tests or bioassays may need to be developed and validated. Screening assays can help to identify the appropriate bioassays for risk assessment and are further discussed in the next section.

Decision: Is proposed treatment scheme expected to reduce/remove stressors of concern?

The aim of this step is to determine whether the treatment scheme is expected to reduce or remove the constituents of concern, or stressors, in the produced water. If stressors can be identified, chemical and physical data, where available, can be used to assess which treatment technology/technologies would likely reduce these stressors. Literature or water treatment models could be used to predict treatment efficacy, however pilot- or full-scale plant data from a similar system may best describe treatment feasibility and should be used if available. To date, limited research targets the full range of specific constituents present in produced water and resulting removal through a treatment train at a full-scale level. While data may exist on removal capabilities of known treatment processes for certain classes of chemicals in other contexts, the chemistry of produced water treatment can be significantly different and therefore may often need to be tested further.

Treatment technologies are discussed at length later in this module and in a table thoroughly assessing available technologies (Appendix 3-E). Developing an appropriate treatment train is a function of understanding the removal capabilities of each technology with respect to defined stressors, specifically those that may pose particular challenges. These may include:

- General water chemistry parameters: high TDS (i.e., greater than sea water) can be difficult/costly to reduce and can limit available technology options; as can ammonia, sulfur, boron, etc.
- Inorganic constituents: heavy metals, which can impact waste character
- Organic constituents: volatile, semi-volatile, and non-volatile organic compounds, some of which may require reduction to trace levels
- Radiological constituents: constituents may co-precipitate and pose challenges for residual waste management

177 See, e.g., USEPA, Whole effluent toxicity methods, https://www.epa.gov/cwa-methods/whole-effluent-toxicity-methods.

The treatment technologies can be assessed using a variety of strategies, including:

- Literature review or desk-top modeling can be used to assess expected constituent removal, including the identification of pre-treatment systems that can increase efficiency of later treatment stages
- Laboratory and bench-scale analysis, potentially including validation with non-targeted analysis and/or bioassays
- Small-scale field pilots
- Full-scale field testing under real-time conditions

All assessment strategies will not necessarily occur during this phase. Instead, this analysis phase will likely focus on desk-top modeling and/or bench-scale testing. If these assessments indicate that there are constituents of concern that the proposed treatment system is not capable of removing, further research may be necessary.

Pilot projects for treatment technologies may serve a useful role in identifying and prioritizing constituents of concern and choosing or designing an appropriate treatment scheme and authorization program. A combination of approaches, like utilizing pilot projects, may be necessary to determine the efficiency of treatment as noted in the risk matrix previously discussed. Pilot projects can help further what might otherwise be complex and costly analysis such as identifying constituents of concern. For example, many of the analytical methods currently available were developed for the analysis of low levels of contaminants in freshwater. Though advanced characterization of untreated produced water is ideal, due to the high concentration of salts and other potential masking components, it may be necessary to utilize existing methods to approximate contaminant levels (or classes of contaminants) in produced water for fit for purpose treatment options. A pilot treatment system could yield treated water which could much more easily use existing and high-resolution methods could be more easily used for more comprehensive characterization. Pilot project data and associated characterization efforts could then be useful to inform an assessment of risk and definition of water quality and reuse objectives. The results could be used iteratively to adjust the treatment technology to provide a final treated water of acceptable quality, while also informing any necessary permitting or authorization processes.

Research Task: Select, develop or refine technologies

Selection or development of an effective treatment system is predicated on the assumption of a well-characterized influent stream with defined treatment goals. Once those prerequisites have been met, treatment selection, design and validation can be completed. Where established treatment processes are considered, they must be assessed for efficacies in treating produced water. Treatment technology development, improvement, and iteration can provide an ongoing feedback into treatment schemes used for various reuse scenarios. As more is learned about the stressors of concern, related risks, as well as potential regulatory requirements and considerations initially proposed technologies may need to be revisited or modified.

- Consider alternative treatment strategies capable of removing stressors
  - Alternative uses of Mature technologies
  - Emerging Technologies
  - Research on New Treatment Technologies
- Conduct treatability studies for specific stressors
  - Bench-scale testing to demonstrate stressor(s) removal (some mature technologies can be severely impacted by produced water constituents, so the need to bench-test may be an important consideration, prior to pilot)

Advancements in treatment technologies are likely to be vital to spur produced water reuse, including new technologies or technology combinations, as well as cost reductions in technology applications that are currently prohibitively expensive.

Research: Pilot testing and effluent characterization

The ability to test treatment trains at pilot-scale to remove constituents of concern from produced water is a critical step in validating a system. This step allows the "risk assessor" to predict chemical concentrations that will be present after treatment and potentially in waste streams. Having this information may allow for an accurate risk assessment. In addition to understanding the efficacy of constituent removal, the objectives of pilot testing also include:

1. Evaluate process performance;
2. Quantify chemical and energy requirements;
3. Identify quantity and character of created waste stream and management plan;
4. Document treated water quality;
5. Assess (short-term) system operability and maintainability; and
6. Develop key design criteria and operating parameters for use in sizing and costing full-scale treatment facilities.

The conclusion of Phase II is expected to result in a more complete understanding of the treatment train and known character of stressors of concern that are being removed into waste streams or that may be expected in the treated water that is intended for reuse (or potentially present in the event of a treatment upset). This is a significant objective and may take noteworthy time and resources to complete. Successful efforts in these iterative research phases, however, will inform risk assessment and management frameworks, and help to prioritize investment in method and technology development, resulting in more efficient efforts to move toward approval and implementation of a specific reuse scenario.

The Salt Challenge. Produced water is a complex waste stream that is often high in total dissolved solids (TDS). From characterization to treatment to solids management, TDS can create inherent challenges that may impact decision-making on how a produced water is reused or otherwise managed. Some of these challenges may be lessened after advanced treatment. Challenges can include:

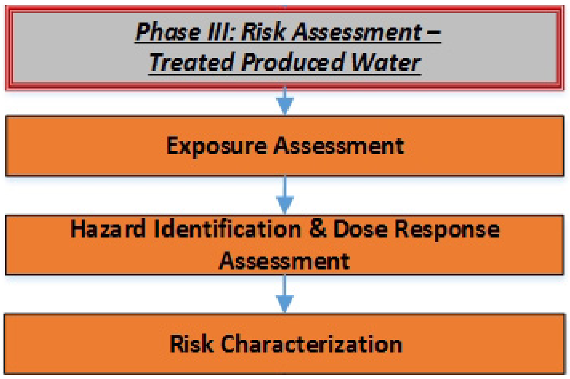
- **Characterization:** Salt content can interfere with analytical methods by enhancing or suppressing the instrument signal or by interfering with other constituents in produced water (matrix interferences), which can lead to biased results.
- **Toxicity assessment:** The presence of moderate to high TDS can mask hazards associated with other, lower concentration constituents. Toxicity tests after treatment should consider residual risks from organic and inorganic compounds, including interactions between constituents (including remaining ions) that may not be well understood. This underscores the need to evaluate whole effluent effects alongside individual constituents. Investigation of toxicity assessment options that are less sensitive to salinity or help to address non-TDS related residual toxicity concerns may be an area of further research need.
- **Risk assessments:** Many risk assessment protocols are oriented toward potential impacts to fresh or marine systems. While many reuse scenarios will involve TDS removal, salts may remain at some level and understanding potential health and environmental impact cannot be overlooked. Low concentration constituents other than TDS that might drive residual risk and may not be identified correctly or might be underestimated. As such, the impact of any TDS and its interaction with other remaining constituents in the treated produced water proposed for reuse should be considered in risk assessment and management strategies.
- **Treatment:** TDS levels can have a significant role on the selection, design, and cost of treatment systems to meet quality objectives.
- **Residuals:** Treatment to remove TDS will result in residual concentrated brines, sludges, or solids, sometimes at very large volumes, depending upon the mechanism utilized. Planning for the management, sale, reuse, or disposal of these residuals is a significant aspect of a reuse project.

Advanced produced water treatment scenarios to meet quality objectives are likely to result in solids and other residual wastes that will require assessment and appropriate management. Assessment of the character, volume, and management strategies of these residuals for further reuse or disposal will be important not only for the entity proposing a treatment strategy, but also for the regulatory entity considering permitting requirements. Some of the considerations that regulators may take into account related to treatment residuals include:

- Depending on the treatment methodology selected, treatment of produced water can result in solid, semi-solid, and liquid residuals, including both wastes and potentially useable products.
- Because of high TDS content and large volumes of produced water, there could be large amounts of these residuals that would need to be managed if treatment of produced water becomes widespread.
- States need to consider the infrastructure needed to manage the treatment residuals.
- The management of treatment residuals may include a combination of temporary storage, surface disposal, underground disposal, and use as a product.
- The content and character of treatment residuals need to be understood in order to evaluate appropriate disposal and/or reuse.
- Regulatory status and ownership of residuals may need to be clarified in some cases. Also, the regulatory status and ownership of any reclaimed products from the treatment residuals would need to be determined.

A note on solids: One potential consideration to mitigate challenges associated with solids management is to design treatment systems that avoid crystallization or the creation of large volumes of solids. For example, designing a system to result in a concentrated brine that could be disposed in an underground injection well. The type and volume of waste expected and considerations for its management, including costs, will play a key factor in decision-making for treatment technologies.

Phase III: Risk assessment – treated produced water



Phase III Overview and Goals: The next phase of this framework moves on from the initial screening assessment and characterization of produced water, pre- and post-treatment, to a more quantitative, site-specific evaluation to aid in the final decision on the acceptability of risk and a decision whether to proceed with the proposed reuse of the produced water as treated. It resembles the EPA framework for risk assessment but is adapted to meet challenges specific to produced water.

The summary of risk assessment included here is to inform the reader of the scope of such a process. This review is not intended to be an exhaustive instructional document, but to bring awareness to the key elements of undertaking a risk assessment.

The EPA *Risk Characterization Handbook*[178] defines the four key steps for human health risk assessment. For each step, the relevant and scientifically reliable information is evaluated and the related uncertainties are described:

a. Exposure Assessment – determination of the extent of human exposure to the stressor;

b. Hazard Identification – determination of whether a particular stressor (e.g., chemical, or mixture of chemicals) is or is not causally linked to particular adverse health effects, typically determined through toxicity assays;

c. Dose- or Concentration-Response Assessment–determination of the relation between the magnitude of exposure and the probability of occurrence and extent of the health effects in question; and

d. Risk Characterization – overall description of the nature and magnitude of health risk due to the stressor(s) under review.

EPA also developed guidelines specific for ecological risk assessment (USEPA 1998) calling for:

a. Problem Formulation – the evaluation of goals, selection of assessment endpoints, preparation of the conceptual model, and development of an analysis plan;

b. Analysis – the evaluation of exposure to stressors and identification of the relationship between stressor levels and effects on ecological receptors; and

c. Risk Characterization – the estimation of ecological risks, discussion of overall degree of confidence in the risk estimates, citation of evidence supporting risk estimates, and interpretation of the adversity of ecological risks.

While problem formulation is not a defined step in the human health assessment process, it is included in the initial planning and scoping of the work. And for this produced water framework, problem formulation is included in Phases 1 and 2, described previously.

Human and ecological risk assessments can be complex processes and typically require specific expertise to be adequately done. EPA and the National Academies of Science have developed numerous guidance documents that strive to stay current with the development of new science. Their guidance helps to ensure that the work is done in a manner that is transparent, consistent and scientifically robust.

Because this framework includes the design of a treatment system as a key pre-step, this Phase 3 process is considered to be a "residual risk assessment," meaning that it will only assess the risk of stressors that are expected to remain in the water following the planned treatment, or those that may be present in the event of a treatment upset or error. If unacceptable risk is identified in this phase, then additional treatment may be required. Phase 4 will account for that outcome.

178 USEPA, *Risk Characterization Handbook*, EPA 100-B-00-002, (December 2000).

Key research steps in a risk assessment are briefly described below.

Research Task: Exposure assessment

The first step of the risk assessment in the Evaluation Framework is a study to identify and characterize the receptors that are likely to be exposed to the stressors in the treated produced water, and to describe the likely exposure pathway(s). In this context of exposure to produced water the term "receptor" refers to living organisms and the environment that supports them. Potential receptors could include humans, livestock, aquatic and terrestrial life, agricultural crops and the soil, groundwater and surface water necessary to support them. The identification of relevant receptors is generally aided by location-specific factors such as regulations, policy, guidelines, and stakeholder interests; for example, from state and regional agencies, agricultural organizations, and local communities. This step of identifying receptors may be done earlier, during the preliminary screening, but if so, the findings should be confirmed at this stage and updated with in-depth chemical characterization data.

Exposure conditions can vary significantly over time for any particular location. Risk assessors and risk managers will need to decide on the full reasonable range for each key exposure variable (e.g., river flow, quantity of produced water provided) to ensure that characterization appropriately covers the range of potential risks.

Exposure pathways describe how stressors reach the receptors. An exposure pathway includes five key elements[179]:

1. Source – how the stressor(s) enter the environment; this includes the spatial and temporal distribution of stressor release and subsequent transport from the source
2. Media – describes the location to which the stressor moves
3. Exposure – where receptors contact the media
4. Route – how the stressor(s) enter the receptor, i.e., via inhalation, ingestion, dermal
5. Receptor – what organisms are present to be potentially exposed

All elements must be present for an exposure pathway to be complete, otherwise, a pathway is incomplete and there is no risk.

Research recommendation: A site-specific conceptual model is recommended to organize and communicate the linkages between stressor exposures-receptor linkages for the intended produced water reuse scenario. In developing such models, it is important to consider specific exposure pathways of concern, such as the degree to which a substance may bioaccumulate in the food chain since this will dictate the relative importance of potential dietary routes of exposure particularly to humans and higher trophic wildlife.

For example, Hagstrom et al. created a theoretical conceptual model for identifying potential exposure pathways for agricultural and livestock watering reuse utilizing produced water (Figure 3-10).[180]

179 USEPA, "Guidelines for ecological risk assessment," (EPA/630/R-95/002F), (Washington, DC: U.S. Environmental Protection Agency, Risk Assessment Forum, 1998), https://clu-in.org/download/contaminantfocus/sediments/ECOTXTBX.PDF. Also, Agency for Toxic Substances and Disease Registry, *Public Health Assessment Manual*, "Chapter 6 Exposure Evaluation," (2005), https://www.atsdr.cdc.gov/hac/phamanual/ch6.html.

180 Earl L. Hagström, Christopher Lyles, Mala Pattanayek, Bridgette DeShields, and Mark P. Berkman, "Produced Water—Emerging Challenges, Risks, and Opportunities," *Environmental Claims Journal* 28 (2):122–39 (2016), https://doi.org/10.1080/10406026.2016.1176471.

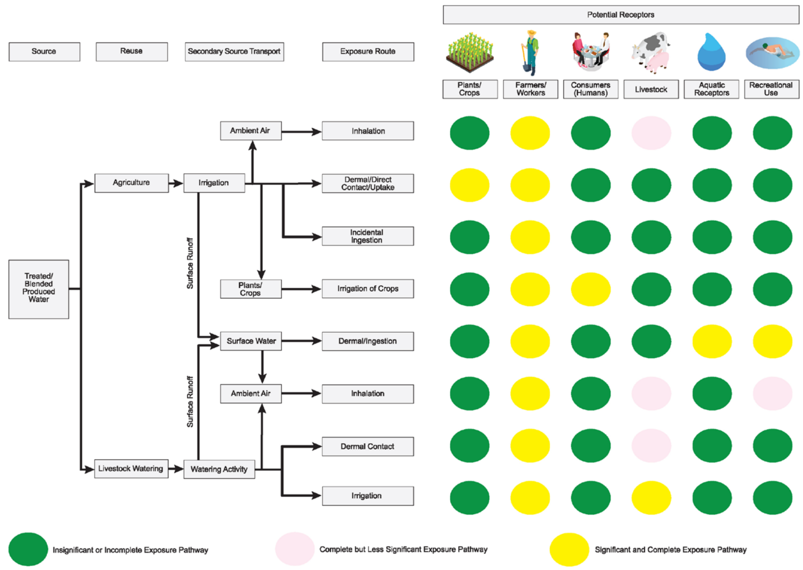


Figure 3-10: Conceptual Site Model for Agriculture and Livestock Watering Reuse

Source: Figure 4 from Hagstrom, 2016

Once the exposure pathway(s), relevant receptors, and stressors are identified, the next major step is to holistically characterize and assess exposure. This involves describing the contact between a receptor and a stressor over time, characterized by the magnitude or intensity (i.e., concentration), frequency (i.e. single, intermittent to continuous), and duration of the interaction (e.g., hours to years). The existence of relevant local receptors indicates the potential for exposure to stressors of concern in produced water, but it does not mean that a receptor is necessarily adversely affected. For adverse effects to occur, a chemical stressor or mixture of stressors has to contact the receptor long enough and at a sufficient intensity to cause the effect. Furthermore, the effect may vary from short to long term, and mild (e.g., reversible change) to severe (e.g., death, reproductive harm). Consideration must also be given to synergistic or additive effects.

Without a clear understanding of the potential for exposure decision-makers will have a difficult task defining the actual risk to the receptors. In many cases much of the information needed to assess exposure will be available from Phase II but it may require expertise to apply it to the situation being considered. In other cases, additional data collection may be needed to adequately define the exposure.

Examples of where research may be needed with respect to produced water may include:

- Defining the persistence, fate, and transport of poorly characterized chemicals in the environment, including abiotic and biotic degradation processes;[181]
- Determining if a chemical bioaccumulates in the receptor over time; e.g., livestock, their feed, or edible crops; and
- Holistically evaluating the capacity and resiliency of local systems (i.e., soils) during or after exposure to the treated produced water.

Danforth et al. identified additional considerations when evaluating long term risks from land application of produced water.[182]

181 Jessica D. Rogers, E. Michael Thurman, Imma Ferrer, James S. Rosenblum, Morgan V. Evans, Paula J. Mouser, and Joseph N. Ryan, “Degradation of Polyethylene Glycols and Polypropylene Glycols in Microcosms Simulating a Spill of Produced Water in Shallow Groundwater.” *Environmental Science: Processes & Impacts* (September 2018), https://doi.org/10.1039/C8EM00291F.

182 C.G. Danforth, J. McPartland, J. Blotevogel, N. Coleman, D. Devlin, M. Olsgard, T.Parkerton, and N. Saunders, “Alternative Management of Oil and Gas Produced Water Requires More Research on its Hazards and Risks,” *Integrated Environmental Assessment and Management*. Accepted for publication, 2019, DOI: 10.1002/ieam.4160.

Research Task: Hazard identification and dose-response assessment

Hazard identification is the scientific process of determining whether exposure to a stressor can cause specific adverse effects. Understanding the potential hazards of constituents that may be in the produced water treated for reuse helps to identify priority concerns. While this process can be a complex, time- and resource-intensive activity, depending on the stressor(s), receptor(s) and adverse outcome(s) being evaluated, risk assessment is predicated on understanding the hazard of potential exposure. Human or animal exposure to a stressor may generate a range of adverse effects, from mild discomfort to organ dysfunction (e.g., kidney, liver), formation of tumors, reproductive impacts, and death, among other effects. Ecosystem impacts can range from reduced biomass or growth of plants to physical or chemical alteration of habitat that reduces or eliminates its capacity to support life.

Regarding hazard identification specific to human health — sources of data may include controlled studies on humans or statistical (epidemiological) studies of human populations to examine whether there is a link between exposure to a stressor and an adverse human health effect. However, these studies of human exposures are rare. Much more common are findings from animal studies (e.g., rodents) where the animals serve as surrogates for humans or other animals that may be exposed (e.g., livestock). These studies range from quick inexpensive screening assays, e.g., *in vitro* assays (cellular, sub-cellular) to costlier, longer *in vivo* (whole animal) assays. *In vitro* methods can provide useful, but limited information on produced water toxicity, while *in vivo* approaches are needed for evaluating complex endpoints that are difficult to assess without whole animal testing. Furthermore, with the rapid advancements in bio-molecular science, scientists are increasingly developing test systems consisting of human cells and computer-based models to determine and, ideally reliably predict, adverse effects of chemicals. This move away from experimental animal studies to more advanced, in-vitro human-based assays will continue and will transform how chemical toxicity testing is done.[183] Examples of ongoing initiatives include the EPA's ToxCast™ program and interagency Tox21 programs.

Different methods are used to study the impacts on ecological receptors. As with human health risk assessment, the methods are numerous, diverse and many are scientifically complex, necessitating expert guidance to credibly complete an ecological assessment. Examples of factors that are often examined include the following:[184]

- What level of the ecosystem is being studied?
  - Individual
  - General population
  - Life stages such as juveniles or adults
  - Different species
- What does the organism do with the stressor (e.g., excrete or accumulate) and how is this impacted by factors such as life-stage, species differences, etc.?
- What are the adverse effects; e.g., changes in reproductive rates, tumors, effects on the nervous system, and mortality?
- How long does it take for a stressor to cause an adverse effect?
  - Acute – right away or within a few hours to a day
  - Subchronic – weeks or months
  - Chronic – a significant part of a lifetime

While human health assessments focus on the potential risks to individuals, ecological assessments most often focus on potential risks to population (e.g., survival, growth) or community (species abundance or diversity) endpoints. The focus and goal of any assessment should be discussed and decided before testing begins.

The hazard identification process for all receptors begins by examining the available scientific data. If there is insufficient or conflicting existing data, then

183 National Academies of Science, *Toxicity Testing in the 21st Century: A Vision and a Strategy Consensus Study Report*, 2007, https://www.nap.edu/catalog/11970/toxicity-testing-in-the-21st-century-a-vision-and-a.

184 USEPA, *Conducting an Ecological Risk Assessment*, https://www.epa.gov/risk/conducting-ecological-risk-assessment (last visited February 24, 2019).

new toxicity studies may need to be conducted. Rapid screening level analyses are often employed initially. This task may include review of chemical hazard reports, *in vitro* assays, and models that predict adverse effects based on chemical structure (Structure Activity Relationship). More advanced screening for aquatic ecosystems rely on Whole Effluent Toxicity and Toxicity Identification Evaluation.

- **Whole Effluent Toxicity (WET).**[185] WET describes the aggregate toxic effect of whole effluent exposure as measured by an organism's response (e.g., lethality, impaired growth, or reproduction). WET tests are meant to replicate the overall effect on aquatic life from exposure to the mixture of stressors present in the effluent without requiring the identification of the specific pollutants. WET testing is a key component to implementing water quality standards under the NPDES permits program in accordance with the Clean Water Act, Section 402. WET limits are often included in permits to ensure that applicable national or state water quality criteria for aquatic life protection are met. WET test methods include two basic types; acute and chronic. EPA recommends running tests using an invertebrate and vertebrate animal, and a plant to identify the most sensitive species for use with the NPDES permits program. *Ceriodaphnia dubia* (freshwater flea) and *Pimephales promelas* (fathead minnow) are examples of EPA approved test species that serve as surrogates used in the achieving protection goals for freshwater aquatic communities. It is also important to note that states may have their own whole effluent testing processes or identified test organisms.
- **Toxicity identification evaluation.**[186] Another more intensive, informative approach that aids in the evaluation of the toxicity of a water sample is Toxicity Identification Evaluation (TIE). The TIE approach is divided into phases. Phase I contains methods to characterize the physical/chemical nature of the constituents which cause toxicity. Such characteristics as solubility, volatility, partition affinity to different sorbents, and filterability are determined without specifically identifying the toxicants. Phase I results are intended as an initial step in specifically identifying the toxicants, but the data generated can also be used to identify treatment methods to remove toxicity without specific identification of the toxicants. Phase II describes methods to specifically identify toxic contaminants, such as non-polar organics, ammonia, or metals. Regulatory agencies typically require in the discharge permit further investigation when there is a WET test failure; if based on accelerated monitoring toxicity persists, a toxicity reduction evaluation may be required that includes a TIE to identify the cause(s) of toxicity. A TIE-type process may also be useful in a research-focused context to assist in identifying constituents of concern after utilizing a whole effluent toxicity test.

Applying these concepts to produced water. The objective in this framework is to develop sufficient evidence to support objective quality criteria for risk characterization for the receptor/stressors of interest. Current tools may not allow for the identification and determination of the toxicity of all constituents in the produced water. Rather, one or some combination of the following approaches can be used, depending on the specific needs as determined by the decision-makers.

- Identify the hazard for key constituents of concern at the maximum potential concentration that is expected for the receptor(s) of interest.
- Conduct toxicity tests on the treated produced water to assess potential for effects at levels of exposure (i.e., for discharge to surface water scenarios, following treatment and expected dilution in the receiving water) expected for the relevant receptors.

185 USEPA, Whole Effluent Toxicity (WET), https://www.epa.gov/npdes/whole-effluent-toxicity-wet (last visited February 24, 2019).

186 USEPA, Methods for Aquatic Toxicity Identification Evaluations, 2nd Edition, EPA/600/6-91/003 (February 1991).

Distillation Treatments and Toxicity. Advanced treatment technologies that drastically reduce total dissolved solids (such as reverse osmosis, thermal distillation, etc.) are effective in removing many constituents of concern but can create additional challenges. For example, removing mineral content can create a water that may pose challenges ranging from corrosion to soil impacts and negative animal health consequences. The lack of minerals can lead to a failure of toxicity tests, such as the WET test because an effluent may be toxic due to the absence of salts or ions required to support aquatic life (i.e., ion imbalance toxicity). Therefore, in some cases, remineralization of the distillate or treated water may be necessary to conduct a WET test or meet other analytical or permitting requirements. See, for example, the modification for low ionic content effluents in Appendix E of CRSD Standard One (given in Appendix 3-D of this report).

Dose- or concentration-response assessments are structured experiments that define the change in adverse response in receptors as the exposure increases. These studies help to determine the "margin of safety" (MOS), which is the ratio of the lowest stressor exposure level that will produce an adverse effect in a receptor (i.e. reference dose) to the predicted highest actual exposure (dose) level. If the MOS is large, then typically, no additional study is needed. On the other hand, if the MOS is below one, then more detailed study could be done to refine the dose- or concentration-response and/or refine the actual exposure in the field. The acceptable MOS may be defined by existing criteria (e.g., water quality standards). If criteria do not exist then new guidelines for selected stressors may we warranted or, where necessary, determined on a location- and case-specific basis by the decision makers. Consideration should be given to background concentrations and consistent methods for site-specific criteria where possible.

Hazard-based research. Toxicity studies may be needed when data is insufficient to assess the hazard. Tools available today can inform this process, though some updating, or advancement may be necessary. Where experimental methods are not available, research may be needed to develop the assay and address the concern before a decision can be made to proceed. Danforth et al. summarized a workshop that was convened to consider knowledge gaps and research needs.[187]

Experts at the workshop identified the need for effects-based testing of produced water, including whole effluent assessments, and concluded that existing frameworks and approaches can inform advancements in produced water toxicity assessment strategies. It was also concluded that research is needed to assess acute and chronic toxicity and long-term risks specific to land application of treated produced water, noting that tools for toxicity analysis in aquatic environments are far more advanced and applied than those for terrestrial environments.

In addition to the lab-based research, efforts will be needed to translate the output of the new assays for use in decision-making-frameworks and guidance for stakeholders. Recently, in an attempt to move away from time- and resource-intensive traditional toxicity prediction assays that rely on animal studies, research has instead begun to focus on high-throughput assays that identify molecular initiating reactions.[188] These molecular reactions may or may not result in organismal disease; therefore, further research is being conducted on how adverse outcome pathways can be developed and used to predict toxicity based on relevant initiating reactions.[189]

More robust research programs could be facilitated by development of a standardized sampling and handling protocol and a centralized repository to manage distribution of produced water samples. Such developments would provide real-world samples for the research community and facilitate comparison across studies and data sets.

187 C.G. Danforth, J. McPartland, J. Blotevogel, N. Coleman, D. Devlin, M. Olsgard, T. Parkerton, and N. Saunders, "Alternative Management of Oil and Gas Produced Water Requires More Research on its Hazards and Risks," *Integrated Environmental Assessment and Management*. Accepted for publication, 2019, DOI: 10.1002/ieam.4160.

188 Jiaqi Lan, Na Gou, Sheikh Mokhles Rahman, Ce Gao, Miao He, and April Z. Gu, "A Quantitative Toxicogenomics Assay for High-Throughput and Mechanistic Genotoxicity Assessment and Screening of Environmental Pollutants," *Environmental Science & Technology* 50 (6): 3202–14 (2016), https://doi.org/10.1021/acs.est.5b05097; Na Gou, Songhu Yuan, Jiaqi Lan, Ce Gao, Akram N. Alshawabkeh, and April Z. Gu, "A Quantitative Toxicogenomics Assay Reveals the Evolution and Nature of Toxicity during the Transformation of Environmental Pollutants," *Environmental Science & Technology* 48 (15): 8855–63 (2014), https://doi.org/10.1021/es501222t.

189 Dries Knapen, Lucia Vergauwen, Daniel L. Villeneuve, and Gerald T. Ankley, "The Potential of AOP Networks for Reproductive and Developmental Toxicity Assay Development," *Reproductive Toxicology* 56 (August 2015): 52–55. https://doi.org/10.1016/j.reprotox.2015.04.003; Rory B. Conolly, Gerald T. Ankley, WanYun Cheng, Michael L. Mayo, David H. Miller, Edward J. Perkins, Daniel L. Villeneuve, and Karen H. Watanabe, "Quantitative Adverse Outcome Pathways and Their Application to Predictive Toxicology," *Environmental Science & Technology* 51 (8): 4661–72 (2017), https://doi.org/10.1021/acs.est.6b06230.

Research Task: Risk characterization

Risk characterization is the final step of the risk assessment process for both ecological and health risks. This step integrates information from all preceding components of the risk assessment and synthesizes an overall conclusion about risk that is useful for decision makers. It will account for the treatment that is planned in Phases I and II above, and the extent to which treatment is expected to reduce the concentrations of stressors in the produced water intended for reuse.

Example: Assessing Risk to the Aquatic Environment. What are intended protection goals associated with produced water discharges?

- Prevent aquatic or soil toxicity impacts to the receiving environment;
- Prevent violation of applicable narrative or numerical ambient quality standards or criteria;
- Prevent endangerment of a drinking water supply;
- Prevent aquatic or terrestrial bioaccumulation to the extent that would threaten human or wildlife health.

How can risk-based permit limits and monitoring requirements be logically developed?

1. Define site-specific produced water quality characteristics.
2. Define applicable environmental quality standards for stressors that are intended to protect intended uses by aquatic or terrestrial wildlife and humans.
3. Conduct initial risk screening of relevant stressors by comparing predicted exposures to environmental quality standards to determine "reasonable potential" for potential risk.

The results from this analysis are used to decide if each quality parameter evaluated poses:

a) low potential risk;

b) uncertain risk due to either no or insufficient quality data; or

c) unacceptable potential risk.

For parameters designated as a) no permit limits are imposed but potential monitoring requirements may be considered to ensure acceptable produced water quality is maintained.

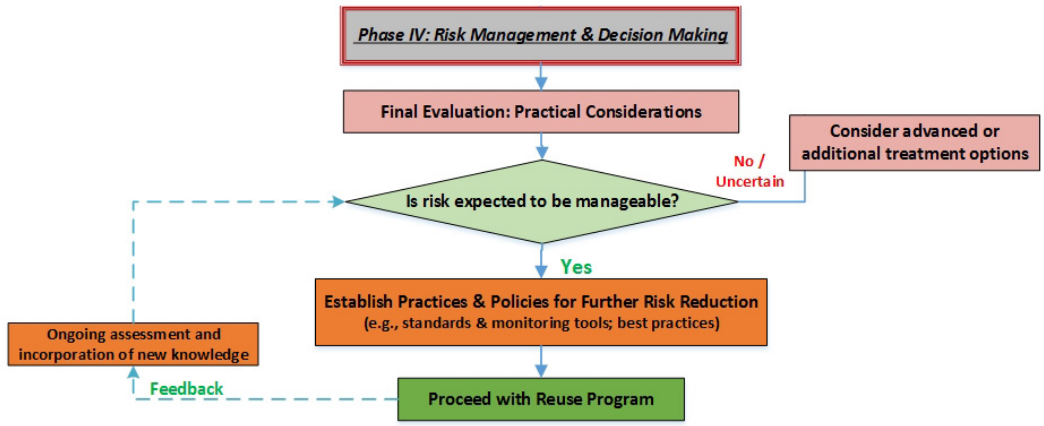
For parameters deemed as b) monitoring requirements are stipulated to refine risk evaluation to determine the need for further permit limits and/or monitoring requirements.

For parameters judged as c) permit limits and monitoring requirements are promulgated.

What produced water treatment is required?

Once permit limits are established, the required treatment technologies for ensuring acceptable produced water quality to support reuse can be evaluated taking a number of considerations into account, including cost, reliability, energy use and waste. See Phase IV for more on this process.

Phase IV: Risk management and decision making



Phase IV Overview and Goals: The Risk Management and Decision Making step will make use of existing and to-be-developed criteria for stressors and receptors of interest. The criteria essentially establish an exposure level that is expected to be low enough to protect valued receptors, e.g., human health, aquatic organisms, livestock, crops or soil. Criteria will already exist for some chemicals of concern that may be present. But for individual constituents of concern that do not have existing criteria, the risk assessment will be helpful for determining what the new criterion should be for each type of receptor.

Final evaluation, practical considerations

As mentioned previously, even where health or ecological risk is deemed acceptable, other considerations such as economics, logistics, or public perception, may result in a decision not to proceed or to modify the proposed project in some way above and beyond that dictated by the risk characterization or regulations. Therefore, at this stage in the assessment, it will be important to look back at the considerations and more thoroughly analyze their potential impact on risk assessment, management, and a decision to proceed with the proposed project.

Decision: Is risk expected to be manageable?

This decision phase takes into consideration the knowledge gained throughout the assessment to determine if the risk is manageable, recognizing that appropriate controls will be incorporated through best practices and permitting requirements that will be applied to the project.

It's important to recognize that a decision on whether risk is manageable and acceptable has several facets. A primary consideration is to whom the risk is considered acceptable or manageable, and by what standards. For example, a rancher or farmer may be concerned about risk to their crop or livestock from an upstream discharge of treated produced water but may not have any authority or input to influence a decision on whether that practice proceeds. It will be important to consider and address all stakeholder concerns as appropriate.

If risk is considered manageable to the decision-maker, the process should move forward to the establishment of the management strategies required. A key factor might be the outcome of risk assessment on treatment effluent as discussed in Phase III. If a conclusion is drawn that concern regarding the treated effluent remains significant, it may be appropriate to consider advanced or additional treatment options, as noted in the framework.

Research/Action Task: Establish practices and policies for further managing risk

There are a variety of mechanisms for further reducing and managing risk beyond treatment requirements. Where new programs for the treatment and reuse of produced water are developed, risk management strategies for ensuring that protective objectives are met and maintained are vital to avoid unintended consequences. Some important considerations for risk management include:

- **Standards.** A need to develop new or modified quality standards and/or permit limitations to address constituents of concern may be present depending upon the reuse context. Data from research and risk assessment phases will be vital in informing standard development, and collaborative information sharing may help to make this process more efficient. Standards also provide a secondary point of information to inform treatment technology goals and objectives. The development of a new standard may also call for the development of an approved analytical method in some cases. Standards to consider might include:

- Effluent limitation guidelines
- Water Quality Standards
- Total Maximum Daily Loads (TMDLs)
- Drinking water Maximum Contaminant Levels, Action Levels, secondary standards or health advisories
- Irrigation standards
- Land application standards

- **Monitoring Tools.** New or modified tools for monitoring can complement standards for newly developing or expanding reuse programs and may allow for ongoing learning while also supporting forward movement to pilot, study, and implement new projects. There may also be opportunities to define constituents of concern that should be monitored in early project/learning phases that may not be tied to permit or standard limitations. Established monitoring requirements can help ensure that permit requirements are consistently achieved by the permit holder. Guidance should also be provided for when monitoring data indicate permit requirements are exceeded, such as during transient upsets in treatment. Tools that might be considered include:
  - Whole effluent toxicity assessment tools or similar bioassays
  - Soil or crop monitoring tools
  - Downstream monitoring stations
  - Influent monitoring to identify unexpected changes

- **Best Practices.** A number of best practices may be identified to further reduce potential risks and may not be tied to specific water quality limitations or standards. Best practices could be implemented by the operator, defined in guidelines by a regulator, or put into practice by an end user. Best practices are often situationally specific, but general guidelines may have wide applicability in some instances. There are numerous examples that may be considered:
  - Preventing or limiting runoff
  - Utilizing drip irrigation
  - Implementing buffer zones, nutrient management plans or improved riparian areas near water bodies
  - Rotating land application sites based on soil moisture content and crop uptake capacity
  - Crop nutrient plans
  - Selection of crops based on contaminant uptake/salinity tolerance
  - Ongoing communication with community stakeholders
  - Batch or truck sampling at delivery to treatment facilities for unexpected quality changes

- **Information Sharing, Reporting, and Disclosure.** As reuse scenarios are more widely implemented, information on their success and lessons learned should be made openly available not only to local governing agencies, but also broadly to inform decision-making in similar circumstances in other regions. Additionally, reporting and disclosure of changes in oil and gas operations, such as key changes in chemical additive packages that may impact the quality of produced water, may be important to proactively address and manage any new or modified risks.
  - One example of this type of reporting occurs in California, where entities that use produced water to irrigate crops report the chemicals used in the production of oil through the issuance of a

13267 order to the Central Valley Water Board.[190] The Central Valley Water Board published responses to the 13267 orders on its website.[191] The Board can issue additional 13267 orders in the future if necessary. This information is taken into consideration in the regulatory programs and in the Central Valley Water Board's ongoing Food Safety Panel.[192]

At this stage, as risks are identified, understood, and managed through treatment alongside established practices and policies for further reduction, decision-makers may conclude that a research program should proceed.

Research Task: Ongoing assessment and incorporation of new knowledge

Available monitoring data, new knowledge, new tools, and other pieces of information should be incorporated into adaptive management and ongoing assessment strategies. If new risks or risk management opportunities are identified, they should be considered in future revisions or iterations on programs, guidelines, or best practices.

Research partnerships between academia, industry, agencies, end-users and other stakeholders should be promoted. A process of continuous improvement to further identify and reduce reuse risks will be better informed by gathering the most current data and information available. As new data are reported, methods are developed, standards are considered, etc. programs for reuse that can be rapidly adaptable to accommodate new information can result in outcomes that even further reduce potential risk to environment and communities.

Dedication to a transparent, iterative process of learning and advancement with a shared goal of encouraging reuse while reducing risk to the furthest extent practicable will help to support expansion of reuse opportunities as well as stakeholder support.

Fit for Purpose: Research Questions and Other Considerations for Varied End Uses

Not all produced water end uses will require the same analysis. In fact, the benefits, risks, and costs associated with reuse scenarios will differ based on the produced water quality and unique circumstances of the end use. Not all questions will be appropriate or necessary for all end uses.

This section presents examples of research questions and other decision-making considerations by end-use types. Examples are illustrative rather than exhaustive, providing a representative overview of "fit-for-purpose" issues that may arise within a decision-making process.

Issues presented are likely to be worthy of research and investigation by interested parties.

Land Applications

Land application scenarios will demand understanding not only of the basic constituents of concern, but also information like concentration, expected uptake rates of ground cover or crops, long-term considerations for soil, and how to prevent harmful chemicals from entering the food supply or water resources at harmful levels. Important research questions or considerations may include:

- What specific constituents may be present at levels of concern for the specific land application or irrigation purpose proposed?
- What are the appropriate agronomic rates of key constituents for various food crops or cover crops to reduce groundwater impacts?[193]
- What are rates of absorption, infiltration, permeability, percolation, etc., in various soil types with various ground cover?
- What best practices or other steps must be taken to limit runoff? What constituents may remain on the surface or at shallow depths that may impact runoff?
- At what rates do irrigated land or crops

190 California Water Code §13267 and 13267.5.

191 Additive Information updated April 2018, https://www.waterboards.ca.gov/centralvalley/water_issues/oil_fields/food_safety/data/2018_0419_additive_info.pdf.

192 California Central Valley Water Board, Oil Fields – Food Safety, https://www.waterboards.ca.gov/centralvalley/water_issues/oil_fields/food_safety/.

193 Agronomic rates are most commonly referenced with respect to beneficial use rates for biosolids and sludges. It refers to the amount of nutrient (nitrogen) needed for the irrigation purpose and yield goals while also minimizing the amount that might pass below the root zone to groundwater.

uptake constituents of concern and are there lethal or sub-lethal impacts?

- Are there strategies for irrigation to reduce run off or other impacts, such as drip irrigation? What about irrigation in urban settings, such as for municipal golf courses, etc.?
- How can long-term impacts to soil biota and soil health be studied or modeled in order to make near-term, protective decisions?
- Assays and other high-throughput/whole effluent rapid analysis tools are limited in the terrestrial environment as compared to the aquatic environment (i.e., whole effluent toxicity tests).[194] How can these tools be expanded to better understand impacts of complex mixtures on soil even where all the potential constituents of concern may not be identified?
- Are there any worker exposure considerations?
- What steps can be taken to reduce the risk of inadvertent consumption or exposure, such as to wildlife and the public?
- What is the resiliency of a receiving ecosystem to adapt to changes in water quality, and are there similar concerns if treated produced water was no longer available?
- Are there potential impacts to groundwater or surface water and how can they be prevented or mitigated?

Water Applications

Reuse scenarios that may impact water resources can come with a host of considerations, varying from impacts to a receiving water body (the water quality itself) to impacts on soils and sediment, aquatic species, surrounding ecosystems, end users, etc. Much of the issues associated with a water application will likely be considered in the permitting process. Considerations include:

- What studies are necessary to model fate and transport of constituents of concern for pathways of interest?
- What is known about the pathways of bioaccumulation, and are there any media (i.e., soils) or species (i.e., fish) that may be more susceptible?
- Understanding the impacts of changes to quantity as well as quality in a water body is critical prior to introducing a new source. Areas for study might include:
    - Impacts to bio aquatic life at various increased flow rates? Impacts of reduction or removal after flows subside?
    - Is there a point where the aquatic community or environment becomes stressed?
    - What is the ratio of discharged flows to other existing flows and does that potentially create an ecosystem impact? How does this differ between an aquifer, river, intermittent stream, seasonal flow, etc.?
    - What is the background level of stressors relative to quality objectives?
- Understanding the impacts of changes to quantity and quality in a ground water aquifer is critical when considering managed aquifer recharge or aquifer storage and recovery. Areas for consideration and study might include:
    - Impacts to wells in the area (irrigation, livestock watering, household wells, etc.);
    - Impacts to movement of water in the aquifer (movement of contamination plumes, changes in quantity and quality of ground water outcropping); and
    - Chemical reactions in the geological formation after injection.
- Understanding the assimilative capacity of a receiving body or aquifer will impact volumes and constituent levels allowed for discharge or injection for reuse based on dilution, mixing, and other factors. Questions include:

194 See, e.g., USEPA, Whole Effluent Toxicity Methods, https://www.epa.gov/cwa-methods/whole-effluent-toxicity-methods (noting that, "Whole Effluent Toxicity (WET) refers to the aggregate toxic effect to aquatic organisms from all pollutants contained in a facility's wastewater (effluent). It is one way we implement the Clean Water Act's prohibition of the discharge of toxic pollutants in toxic amounts. WET tests measure wastewater's effects on specific test organisms' ability to survive, grow and reproduce.").

- What are the designated beneficial uses of the water body or aquifer and will they be impacted?
- What are the characteristics of the receiving system? Will water flow downstream and mix with other discharges or into a lake or other end "sink" where the water is held for a longer period? Do constituents of concern vary based on fast or slower moving systems?
- What impacts are there to other uses due to injection for managed aquifer recharge or aquifer storage and recovery? Will the injection of treated produced water increase the quality of the aquifer and thus change its classification from "saline" to "marginal" quality or from marginal quality to USDWs?
- Will the receiving body allow for a large dilution and mixing rate, or will the discharged treated produced water make up a majority of water flowing into an intermittent stream or water way? What are the impacts of the proposed discharge to the receiving body?
- What additional considerations are necessary to ensure that flows and quality levels are acceptable to maintain designated beneficial uses?

- Crossing of regulatory boundaries may complicate the permitting of produced water discharge and reuse. Questions may include:
  - What are the implications of discharges into a water body that may cross jurisdictional boundaries?
  - What are the implications of the injection of treated produced water into a large aquifer that lies beneath multiple states?
  - Is there a process to resolve conflict that might arise through the transfer of water across jurisdictions for various purposes?
  - Who owns produced water and does that change if it becomes a product rather than a waste?
  - What agencies may need to be involved?
  - What are the differences in the regulatory controls and transboundary transfers if produced water is reused through direct application, aquifer recharge, or surface discharge?
- Considering impacts on a broader watershed or water system will be vital in understanding not only the appropriate limits for a specific treated produced water discharge or aquifer injection, but also the implications on the larger system due to a new industrial discharge coming online in a region. Permit conditions may be established based on upstream and downstream conditions, and limits derived from Total Maximum Daily Loads (TMDLs) may be applicable to address impairments for specific constituents. If conditions change, there may be broader long-term considerations for future permitting.

  Surface water examples include:

  - What implications may occur for other municipal or industrial discharges if flow or character of upstream or downstream segments changes?
  - Are new numeric or narrative permit limits appropriate?
  - Could treated produced water discharges improve the water quality conditions or create additional impairments?
  - Would there need to be a change in the biomonitoring species for other discharges in the water body or stream segment, and what would the appropriate species be?
  - How does ionic balance or mineralization change in a stream segment and are there implications for other discharges?

  Groundwater examples include:

  - What implications will there be for other injection sites in the aquifer with the addition of a new injection point and source?

- Will there be a need for volume reduction or enhanced treatment for others injecting in the aquifer?
- Is there an adequate and appropriate method to account for treated produced that is expected to be recovered for later use?

- Discharges may eventually find their way to a water body used for a public or private water supply or designated for emergency water supplies. Therefore, potential risks for drinking water treatment facilities, such as the formation of disinfection byproducts, altering the basic water chemistry causing corrosivity concerns with lead and copper, and other general scaling or fouling of equipment should be considered.

Lessons from Historic Practices. In some cases, both historic (e.g., unconventional produced water treated by POTWs and some CWTs) and relatively recent and ongoing (e.g., conventional sources to CWTs) permitted discharges have been shown to have negative consequences — often due to inappropriate or inadequate treatment specifically for produced water. Studies of such impacts present valuable learning opportunities, and some improvements can be seen where regulatory programs and industry practices adapt to identified challenges.* Studies such as the few highlighted here are not exhaustive, but do help to underscore the importance of careful consideration of the quality of different influent streams, appropriate fit-for-purpose technologies, and permitting programs in order to avoid unanticipated short and long term impacts in the future.

One identified challenge has been the management of compounds like radionuclides that can bioaccumulate in biological systems or selectively partition into the sediment in ways that aren't always easy to predict. For example, a recent study has found strontium accumulation in the shells of freshwater mussels, which are hypothesized to indicate a long-term impact of historic surface water discharges in Pennsylvania.** The authors indicate a next step will include a soft tissue investigation to better understand whether there may be impacts higher up the food chain for animals that may feed on the mussels. A second study in Pennsylvania focused potential ongoing impacts from discharges of treated conventional produced waters that continued after state limitations were made on unconventional produced waters in 2011, and found accumulation of radioactivity in sediment near discharge sites from 2014–2017 that far exceeded radiation in upstream sediments.† This and additional studies at Pennsylvania sites have also indicated that stream chemistry, which can make radium less bioavailable, can also make it more mobile and may lead to elevated concentrations of radium above background levels downstream.†† Studies have also measured elevated radium levels at discharge points in Wyoming, where produced waters are typically much lower in radioactivity.± Overall, studies such as these emphasize the opportunity to utilize research to learn and adapt practices to reduce impacts that may have been unforeseen, although the scale of historic and ongoing impacts and how these elements may be mobilized, is still under study and worthy of further investigation. A key challenge is interpreting such information in an objective, risk-assessment context.

* William D. Burgos, Luis Castillo-Meza, Travis L. Tasker, Thomas J. Geeza, Patrick J. Drohan, Xiaofeng Liu, Joshua D. Landis, et al., "Watershed-Scale Impacts from Surface Water Disposal of Oil and Gas Wastewater in Western Pennsylvania," *Environmental Science & Technology* 51 (15):8851–60 (July 12, 2017), https://doi.org/10.1021/acs.est.7b01696 (showing through core studies that studied sediment impacts correspond to years prior to regulatory change and decrease over time); see also Van Sice et al., below, which found that loading of radium at discharge sites decreased by an estimated 95% after unconventional discharges at the studied sites ceased.

** Thomas J. Geeza, David P. Gillikin, Bonnie McDevitt, Katherine Van Sice, and Nathaniel R. Warner. 2018. "Accumulation of Marcellus Formation Oil and Gas Wastewater Metals in Freshwater Mussel Shells." *Environmental Science & Technology* 52 (18):10883–92 (September 4, 2018), https://doi.org/10.1021/acs.est.8b02727; also https://news.psu.edu/story/543054/2018/10/22/research/fracking-wastewater-accumulation-found-freshwater-mussels-shells.

† https://nicholas.duke.edu/about/news/radioactivity-oil-and-gas-wastewater-persists-pennsylvania-stream-sediments. Also, Nancy E. Lauer, Nathaniel R. Warner, and Avner Vengosh, "Sources of Radium Accumulation in Stream Sediments near Disposal Sites in Pennsylvania: Implications for Disposal of Conventional Oil and Gas Wastewater," *Environmental Science & Technology* 52 (3): 955–62 (2018), https://doi.org/10.1021/acs.est.7b04952.

†† Katherine Van Sice, Charles A. Cravotta, Bonnie McDevitt, Travis L. Tasker, Joshua D. Landis, Johnna Puhr, and Nathaniel R. Warner, "Radium Attenuation and Mobilization in Stream Sediments Following Oil and Gas Wastewater Disposal in Western Pennsylvania." *Applied Geochemistry* 98: 393–403 (November 2018). https://doi.org/10.1016/j.apgeochem.2018.10.011.

± Bonnie McDevitt, Molly McLaughlin, Charles A. Cravotta, Moses A. Ajemigbitse, Katherine J. Van Sice, Jens Blotevogel, Thomas Borch, and Nathaniel R. Warner, "Emerging Investigator Series: Radium Accumulation in Carbonate River Sediments at Oil and Gas Produced Water Discharges: Implications for Beneficial Use as Disposal Management." *Environmental Science: Processes & Impacts*, (November 2018). https://doi.org/10.1039/C8EM00336J.

Industrial Applications

Treating and reusing produced water as a source of intake water, or feed stream, for industries may provide opportunities to reduce fresh water consumption or supply raw materials. However, significant considerations may be necessary to ensure that changes in water source or feed streams do not inadvertently have negative implications for industrial outcomes or operations. Some of these may include:

- Process implications due to a change in the character of source water, such as scale deposits in piping or other units, cooling towers, pumps, etc.;
- Modifications in the character and required management and disposal of residual wastes, sludges or used fluids;
- The need for additional pretreatment before use;
- Changes in effluent that may result from influent changes and the potential for necessary permit modifications to monitoring limits or discharge allowances under existing permits due to a change in conditions;
- Market considerations for the use of products mined from produced water – i.e., lithium, salt – and whether market values may be modified by an influx of product locally or nationally; and
- Worker safety and exposure considerations for handling new water sources or feed streams and others.

Case Study: Soil Considerations in Oklahoma. The Oklahoma Conservation Commission (OCC) has a program on Healthy Soils and shared some perspective on healthy soils and produced water, adapted here from an email. Healthy soils have greater capacity for water infiltration, reduce erosion, and reduce need for fertilization and pesticides, thereby protecting water quality and restoring a more natural watershed. Five basic principles that support soil health include minimizing disturbance, maximizing plant diversity, maintaining a live plant root, maximizing vegetative cover, and integrating livestock. For the soil health program (or conservation programs in general) to support the use of produced water application to agricultural lands, questions need to be answered, including:

- **Salinity:** Many agricultural fields in Oklahoma already are challenged by areas of high soil salinity. Areas with the greatest need for irrigation may already have higher than desired salinity due to current and historical irrigation. Also, as irrigation technology improves to deliver more water to the plant than the atmosphere in the field, there is potential for mineralization to impact piping and delivery sprayers. Before most producers would be comfortable with produced water application, they would need to see regional demonstrations as well as studies showing how various crops would be affected during various environmental conditions, e.g., if irrigation is done during a dry period vs. a wet period and, how are plant growth and soil salinity affected? What produced water application rates in various regions, soil types, and weather patterns result in no significant decrease in vegetative growth or increase in erosion rates? How would irrigation with or land application by produced waters affect healthy soils vs. soils with lower organic content and biological activity?
- **Producer and public concern:** Although produced water differs significantly from hydraulic fracturing water, many people will be concerned with the potential for production chemicals as well as the natural petroleum compounds, heavy metals, radionuclides, and other dissolved and volatile organic compounds contained in the water to impact or be accumulated in livestock, crops, or other vegetation. Studies and demonstrations will need to evaluate how this can be safely done with minimal risk, but also preferably with some benefit to the agricultural operation. Many agricultural producers will only accept a practice after it has been demonstrated to them that it works in their region, with their soils, climatic conditions, and type of agricultural system.
- **Environmental impacts:** The agricultural industry is already heavily scrutinized for their potential and real environmental impacts. Many farmers, agricultural product users, as well as conservation professionals will be concerned with the results from land application of produced waters and what impacts that will have on downstream water quality. Questions will need to be answered with respect to where, when, and how much land application of produced water has no measurable impact to runoff water quality.

Livestock, Wildlife, and Other Consumption

Studies in literature address the potential implications for livestock and other wildlife from consumption of different pollutants, minerals, constituents, water, etc., although few are directly devoted to treated produced water (see "State of the Science: Literature Review"). Specific considerations include:

- How best to determine safety of certain treatment levels for a variety of consuming species?
- What does literature say with respect to salinity and TDS levels? Are those studies fitting or appropriate for the receptors of interest?
- Are there potential chronic, sub-lethal effects that should be taken into consideration? If so, at what levels?
- Are some species more susceptible to toxic effects or bioaccumulation? What potential food-chain considerations may be at play for higher order species?
- Are there ecosystem considerations if discharges are not long-term, sustainable, or reliable?

Other Practical Considerations and Research Opportunities

For any decision on produced water treatment and reuse, many considerations are at play above and beyond scientific research on health or environmental risk, including laws and regulations, public perception, logistics, economics, and additional environmental considerations, as well as the anticipated benefits of the reuse. Analysis of these broader costs and benefits is likely to occur before or alongside risk-assessment research. Alone or collectively, these additional considerations can be decisive. Study of these topics may be called for in the near-term as progress is made on treatment technologies as well as health and environmental considerations.

Content for this section was developed in collaboration with industry and regulatory project participants who contributed to brainstorming on priority issues. The ideas shared here are illustrative, but not exhaustive.

Legal and Regulatory

Many considerations related to law, regulation, permitting, and policy are covered in Module 1 of this report. Following are a few key considerations related specifically to the decision-making process for reuse or release outside oil and gas operations.

What permits or authorizations may be required?

While it is possible that some reuse scenarios may not require permits, permitting and authorization will be a major consideration for many reuse strategies, particularly where existing permitting or regulatory structures and guidelines are limited. Permits or other authorizations may come into play at the federal, state, and even local level depending on the proposed project and may be required from multiple entities. For pilots and full-scale practices, impacts of these authorizations can range from determining whether, when, where, and how a practice can proceed at all, to defining the data and information necessary to establish limits or monitoring requirements. Data limitations may present challenges for permit writers in crafting permits that are confidently protective of human health and the environment. Permitting and authorization structures must also tackle a wider range of considerations, including:

- **What agency or agencies have authority?** In many states, current regulatory language or memorandums of understanding between agencies do not clearly define who may have the authority to control or permit a given alternative use. Different uses may result in different agency involvement and different authorities, regulatory programs, or permits may be required for multiple stages of a proposed project, from storage and treatment to transport and final use. Some are working through these questions, including Colorado, Pennsylvania, Oklahoma, and New Mexico.
- **Who has ownership or water rights for produced water, treated water?** Clarifying who owns the water, what it means to take possession/custody of water, and whether there are valued water rights attached to a 'new' water available for use is a vital prerequisite to moving forward on a project. In many states, these issues are not currently settled in the context of produced water but are likely to play a significant role in decision-making due to the impact a particular result may have on everything from reuse authority to economics

and liability. States may reach differing conclusions on these questions.

- **How is produced water defined?** Whether produced water is considered a waste or a resource, surface or groundwater, mineral or non-mineral, etc. will play a role not only in permits and authorities for reuse projects, but also in economics. For example, might a produced water treated for sale and use outside oil and gas operations — and therefore, transitioned from waste to valued resource — require a royalty payment to a mineral or surface owner? These questions are not yet fully answered.
- **Are additional permits necessary to implement reuse, i.e., infrastructure?** Reuse scenarios that involve transport outside oil and gas operations are likely to require new or expanded infrastructure like storage, transportation, and treatment facilities. This infrastructure may often require permitting, and the timelines and requirements for such infrastructure may play a significant role in whether and when a project moves forward.

Who has liability and is liability transferred?
Liability is a significant consideration in scenarios of treating and reusing produced water outside oil and gas operations. Views vary widely within the oil and gas industry as to willingness to assume liability and within regulatory authorities as to where liability may or may not change hands in reuse scenarios. Concerns regarding both short- and long-term liability play a major role in decision-making on whether to move forward with a project. Some companies may be satisfied that liability and ownership is likely to transfer to a third-party treatment company or final users, while other companies' legal departments may put higher hurdles in place due to the risk that longer-term future impacts (like soil degradation over a decade time frame, or newly discovered constituents of concern not previously analyzed or limited) may be traced back to the company. There are also potential concerns with basic liability for waste management (where produced water is classified as a "waste"), and what may occur when produced water leaves oil and gas operations and the third party with custody of that waste mismanages it. The way in which liability is assigned may impact how or whether certain reuse projects proceed.

Numerous other legal and regulatory considerations may require attention, analysis, and adaptation if alternative uses are to be considered more widely in the future. Some are discussed in more depth in Module 1, and others may not yet be identified.

Public Perception
Public perception is an undeniable consideration not only for oil and gas activities in general, but also for reuse of any wastewater, not just treated produced water. Local communities are often extremely active when it comes to protection of natural resources. Where scenarios may be in place to release treated produced water for reuse in ways that may have a broader set of potential impacts, like watering crops or local road application, public perception is likely to play a major role in the way decisions are made.

Just as research and risk assessment will need to be conducted in a localized, site-specific way, so too will public communication and perception management.

How to best manage public perception will depend on local dynamics and pressures. In some regions, public perception may involve a balance between concerns over current produced water disposal options like disposal wells and newer proposed alternatives for treated produced water like discharge or agricultural use. For example, local communities with significant concerns regarding induced seismicity, may be more open to consider reuse opportunities. The same may be true for communities facing drought intensity or fresh water scarcity. Where options are limited, the public may be more open to consider alternatives, though transparency and communication will still be key. There have been a few limited studies of public perception specific to the reuse of "desalinated" produced water (broadly defined in participant interviews as "a process by which salt and other contaminants are removed from the water") for various purposes both inside and outside oil and gas operations. These studies, conducted in Texas and Pennsylvania, have concluded that familiarity with technology results in greater comfort with reuse, and that respondents are generally more "favorably disposed" toward reuse options that reduce the probability of human or animal ingestion.[195]

Public perception, concern, and attention regarding produced water and wastewater reuse — even if heightened due to association with oil and gas development — is not unique to this industry. In fact, one of the leading challenges of wastewater reuse internationally is public perception, as projects on other types of wastewater reuse have demonstrated.

- **Risk communication is vital.** Beyond a one-way conversation to educate stakeholders, risk communication entails a two-way opportunity to gather information on perceived risk and to deliver information that addresses concerns. Clarity and care in messaging are important.
- **Mitigation measures should be clearly explained.** In some cases, it is helpful to present information about the barriers and mitigation measures available to increase the safety of reuse. A barrier might include natural or artificial dividers between a discharge and an eventual end-use such as rivers and streams or constructed impoundments or wetlands. Such measures can modify perception of the immediacy of impact and better incorporate a treated discharge into a larger water system.
- **Transparency is key.** Data and information sharing of any and all evidence that a wastewater can be safely or successfully reused is relevant and informative to public perception. Transparency is vital and data from labs to pilot scale fields studies should be shared, even where results indicate more work needs to be done. Stakeholder acceptance can be increased through transparent communication and collaboration with local scientists, politicians, and other business or social leaders.

For municipal wastewater treatment plant effluent, constructing buffers between where the water is generated or treated to where the water enters a surface water body or ground water aquifer either through percolation or injection has led to much greater acceptance. For example, the North Texas Municipal Water District constructed a wetland for the treated effluent to flow through prior to entering a lake. Walking paths and a water education center were constructed in the wetlands area allowing the water district to educate the public about water, its uses, treatment, and beneficial reuse. Additionally, a new space was created for use by school groups and civic organizations that ultimately helped gain acceptance of the reuse concept.[196] Oil and gas companies and regulatory agencies may find this model useful in gaining public acceptance of a given discharge or reuse project, particularly in more urban areas.

Public concern can be a forceful motivation to change or modify decisions on produced water reuse outside oil and gas operations and should be addressed as early as possible in any proposed project. Public involvement or perception not only will relate to health or environmental risks but may also relate to increased infrastructure required for extensive reuse projects like trucks, pipelines, impoundments, or treatment facilities. In California, public concern and questions regarding health and environmental impacts of reuse have led to demand for significant new research and action.

195 G.L. Theodori; B.J. Wynveen; W.E. Fox, D.B. Burnett, "Public Perception of Desalinated Water from Oil and Gas Field Operations," *Soc and Nat Res 2009*, 22:674-685; G.L. Theodori; M. Avalos, D.B. Burnett; J.A. Veil, "Public Perception of Desalinated Produced Water from Oil and Gas Field Operations: A Replication," *J Rural Social Sciences* 2011, 26(1): 92-106; G.L. Theodori, A.E. Luloff, F.K. Willits, D.B. Burnett, "Hydraulic Fracturing and the Management, Disposal, and Reuse of Frac Flowback Waters: Views from the Public in the Marcellus Shale," *Energy Research & Social Science* 2014, 2: 66-74.

196 https://www.ntmwd.com/.

Agricultural Reuse of Produced Water in California. California produced approximately 175 million barrels of oil onshore in 2016, along with nearly 2.73 billion barrels of produced water.* Interest in produced water reuse has grown due in large part to the ongoing drought. Reusing produced water in irrigation, which has occurred in eastern Kern County for over three decades, has expanded in recent years.** Produced water here contains low concentrations of total dissolved solids and boron, making reuse more feasible than in areas with higher salinity.

Concern over produced water reuse for agricultural irrigation has arisen in recent years and prompted the Central Valley Regional Water Quality Control Board (Central Valley Water Board) to develop a Food Safety Expert Panel (Panel). The Panel's purpose is to guide sample collection and analytical methods for field studies, assess results, identify data gaps, and procure practical outcomes regarding produced water management. The Central Valley Water Board will consider the Panel's recommendations to regulate produced water reuse. Panel meetings are typically held quarterly and are open to the public. The meetings are attended by industry and environmental stakeholders as well as regulators.

In the three years since the Panel's inception, multiple crop sampling events and an irrigation water quality evaluation were conducted in vicinity of the Cawelo Water District, where produced water is currently reused to irrigate crops under a permit issued by the Central Valley Water Board. The Central Valley Water Board has also received chemical disclosures from operators and suppliers through informational orders (California Code § 13267). These disclosures are available to the public on the Central Valley Water Board's website† and are being evaluated and incorporated into future sampling efforts. The oilfield chemical additives evaluation is ongoing since several chemicals do not have standardized sampling methods, making water monitoring and crop plant uptake quantification difficult. However, community representatives and Panel members share an interest in evaluating and quantifying chemical additives when feasible and conducting health risk evaluations before the Panel provides its final recommendations.

* Department of Conservation, Division of Oil, Gas, & Geothermal Resources. 2017. 2016 Report of California Oil and Gas Production Statistics. ftp://ftp.consrv.ca.gov/pub/oil/annual_reports/2016/2016_Annual_Report_Final_Corrected2.pdf.

** Food Safety – Oil Field Wastewater Reuse Expert Panel. 2017. Project Charter. https://www.waterboards.ca.gov/centralvalley/water_issues/oil_fields/food_safety/information/offsep_charter.pdf.

† Central Valley Regional Water Quality Control Board. 2018. Oil Field – Food Safety. https://www.waterboards.ca.gov/centralvalley/water_issues/oil_fields/food_safety/index.html.

Logistical Considerations

Any new produced water management option, especially involving reuse outside oil and gas operations, will require the operator, end user, and any midstream third-party to consider logistics. These should likely be assessed early in the decision-making process because they may significantly change the economics or feasibility of a project.

- **Timing.** In some cases, reuse will be practically or economically feasible only where the new water supply coincides with local water demand. Even where demand is present, many end users require long-term, reliable, consistent quality water supplies, particularly if they may be making business decisions to move away from another reliable source. Other end users, such as farmers, may only require volumes of water on a seasonal timeline. These temporal demands may prove challenging under oil and gas operational dynamics in which produced volumes and quality can vary significantly overtime, areas of heavy production may move, ownership of wells may change hands, etc. End-user industries and businesses may not be able to be as flexible as the oil and gas industry.
- **Infrastructure.** Depending on the location of an end user relative to produced water sources, new or expanded storage and transportation options may be required. Additionally, meeting a variety of water quality requirements will necessitate treatment facilities and

related infrastructure not only for the treatment technologies themselves, but potentially also for residual waste management (like landfills). Such infrastructure needs not only impact economics of particular reuse scenarios, but also play a role in public perception as well as risk, and liability for potential issues like spills. Where produced water transport occurs, practices for loading, unloading, pipelines, etc. aimed at reducing or preventing spills should be considered and incorporated. For operational reasons, and to reduce transportation risks, produced water is likely to be treated near the source.

- **Operational decisions.** The end use planned for produced water may have an impact on upstream operational decisions. For example, operators may design drilling or hydraulic fracturing chemistries to avoid using or creating a chemical of concern that is challenging or costly to remove through treatment and poses a risk to the environment or health if released. Or, companies may decide to invest in water treatment rather than constructing disposal wells in certain areas. Operational decisions may also demand modification for end users. For example, a farmer or rancher interested in the potential to use treated produced water may consider planting a different type of crop.

Economic Considerations

Economic considerations come into play for any produced water management scenario. Even where scientific studies, regulations, liability, and public perception point to the feasibility of reuse, cost is likely to be a deciding factor. Industry operators will have to convince their business units that reuse will create value relative to status quo produced water management, while end users will need to be convinced that using treated produced water is an economically sound and reliable alternative for their use or business. The question, on a case-by-case basis, will be whether benefits or opportunities outweigh the price tag. In some cases, opportunities for reuse may come with opportunities for economic gain.

Economic considerations regarding produced water management are addressed in Module 2 and a discussion of water rights related to reuse is included in Module 1. Additional considerations relevant to reuse outside oil and gas operations include:

- **Treatment.** Treatment is an obvious economic consideration for alternative uses that demand high quality waters. Advanced treatment can be costly, though there are some technologies in development with promise of significantly reducing that cost and can skew economics away from reuse unless there are cost or incentives to offset the price differential between disposal or in-field recycling and a use outside oil and gas operations.
- **Transportation, infrastructure and logistics.** Storing, moving, and managing produced water and treated water for reuse outside oil and gas operations requires investment in transportation, infrastructure or other related logistics. Infrastructure will require upfront investment, which may or may not be annuitized over the life of a well (because water may not be produced consistently). Economics on logistics and infrastructure may demand long term commitments or multi-operator cooperation, adding not only cost but operational and financial complexity. Cost and logistics for storage and transport (as well as risk and permitting requirements) will likely vary significantly for treated versus untreated produced water. For example, produced water treated to meet Pennsylvania's "dewasting" standard[197] can be stored and transported like fresh water prior to being used to develop or hydraulically fracture an oil or gas well, which can reduce both risk and logistical costs (though that must be balanced with the economics of treating to that standard). Cost analyses of transportation infrastructure such as pipelines will consider the value of the water for the end user. The Oklahoma Produced Water Working Group report found that the value of water to users is often dramatically less than the cost to

197 Pennsylvania WMGR123, described further in regulatory section herein.

transport it.[198] This dynamic is one reason why discharge to surface water may be investigated prior to long-distance pipelines as a delivery mechanism for reuse.

- **Contracts, agreements, long-term commitments, royalties, and 'sunk costs'.** The basic decision to change an existing practice for waste management can itself come with a cost. In many cases both operators and potential end users have existing contracts or agreements for the purchase and use of water resources, many of which may be long-term or tied to production rights on a lease. If these costs are already "sunk," the economics of looking at alternatives are impacted. Additionally, water supply is increasingly tied to surface use agreements between operating companies and surface owners. This can create additional challenges.

Example: Contracts and Agreements. Pioneer Natural Resource and the City of Midland entered into a contract in 2016 for Pioneer to take and pay for treated municipal water for use in oil and gas development. The full project, including treatment plant upgrades is estimated at $133.5 million. The Midland contract is volume based with a primary term expected to last for 20 to 28 years depending on flow rates.* Pioneer has a similar contract with the City of Odessa with an 11-year, $117 million term.**

* City of Midland News Release, "City Council Approves Pioneer Agreements," (June 19, 2018), https://www.midlandtexas.gov/CivicAlerts.aspx?AID=956&ARC=1696.

** Pioneer News Release, "Water Project to Save Millions of Gallons of Freshwater Throughout Permian Basin," (January 2016), http://investors.pxd.com/news-releases/news-release-details/water-project-save-millions-gallons-freshwater-throughout.

Long-term commitments are also a consideration when it comes to contracting with a third-party treatment provider. Many such providers may ask for multi-year agreements to either provide or purchase water in order to manage operational economics, but such agreements may be risky for operators (if regulation changes, downturns reduce produced water volumes, operators are sold, etc.) or end-users (if quality changes impact business, regulation changes, etc.).

Potential economic risks are also associated with uncertainty surrounding the regulatory classification of treated produced water as a waste or valuable product. For example, produced water is treated as an oil and gas related waste today and operators carry the cost of managing and disposing of that waste. If produced water were to become a valuable product, it is unknown whether a new cost such as a royalty may be attached.

- **Energy.** Energy demand and supply could play a major role in decision-making for reuse alternatives, particularly where heat- or power-intensive treatment technologies are required. This consideration requires not only an analysis of the cost of power, but also the cost of getting power where it is needed, such as the costs of generators or transmission lines. Research should be done to better model implications on energy demand, supply, and cost for reuse scenarios.[199] Additionally, investigation of the opportunity to utilize waste energy[200] or co-located renewable energy resources is appropriate.

198 Oklahoma Water Resources Board, "Water for 2060 Produced Water Working Group," https://www.owrb.ok.gov/2060/pwwg.php.

199 See, e.g., K. Zemlick, E. Kalhor, B.M. Thomson, J.M. Chermak, E.J. Sullivan Graham, V.C. Tidwell, "Mapping the energy footprint of produced water management in New Mexico," *Environ. Res. Lett.* 12 024008 (2018) https://doi.org/10.1088/1748-9326/aa9e54 (comparing energy demand for sourcing and transporting fresh water for use in hydraulic fracturing to energy demand to move treated produced water to a point of reuse for hydraulic fracturing).

200 See, e.g., Y.R. Glazer, J.B. Kjellsson, K.T. Sanders, M.E. Webber, "Potential for using energy from flared gas for on-site hydraulic fracturing wastewater treatment in Texas," *Environ. Sci. Tech. Lett.* 1(7) p.300-304 (2014), DOI: 10.1021/ez500129a.

- **Markets.** Markets factors are likely to be unpredictable. For example, while the perceived or predicted market for solid products often play a role in current treatment technology expected valuations, those markets may not actually exist in a region, may change drastically over time with the influx of new product quantities, or may not be viable if solid products are not proven to meet purity standards and regulatory requirements. The products produced and potential hazards (particularly transportation risk) should be reviewed. Another example is the market for water and water rights. Facilities that may accept and treat produced water for surface discharge may seek opportunities to gain an additional income stream from the creation of new water rights. This will require not only a market and user for that water, but also a regulatory structure for prescribing a value to treated produced water – neither of which exist in most states today. If fee structures for third-party water managers or treatment providers incorporate theoretical rebates for monetary benefits gained from the sale of products on market, operators may not be willing to take that risk, or may not recommit in the future.

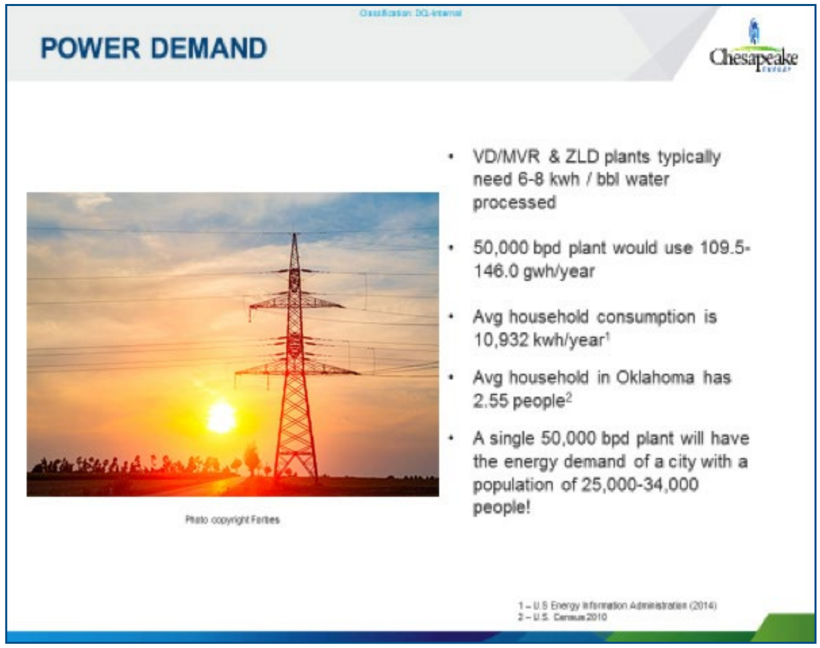


Figure 3-11: Example overview of expected power demand for advanced treatment and desalination plants as compared to other energy users

Source: Chesapeake Energy

- **Solids management.** Advanced treatment of produced water, in many cases, will result in large volumes of residual solids unless systems are designed to avoid this outcome (i.e., produce a heavy brine waste stream for injection). Some of these may be marketable if of pure quality and permitted, but this may not always be the case, and may not be a reliable long-term business plan. Large volumes of salts would also have to be transferred to the correct markets via rail, truck, etc. which impacts economic outcomes. Therefore, the volume of solids produced and considerations for its management will play a role in decision-making for alternative uses, particularly those that require distillation or crystallization. Solids management can have a logistical component, such as where large volumes of salts or other residual solids can be stored or disposed. On the other hand, solids management can also come with high cost.
- **Water rights.** Water rights are a key consideration with respect to reuse of produced water. See Module 1 for a more substantive discussion.

Capacity		Products and waste			
bbl/day	MGD	Filter Cake (tons/day)	Distillate (bbl/day)	Salt (tons/day)	$CaCl_2$ Brine (bbl/day)
5,000	0.2	53	4,000	107	1,000
50,000	2.1	533	40,000	1,066	10,000
100,000	4.2	1,066	80,000	2,132	20,000
200,000	8.4	2,132	160,000	4,264	40,000
300,000	12.5	3,198	240,000	6,396	60,000

Table 3-2: Estimated Waste Products and Volumes from Produced Water Treatment at Varying Volumes

Source: Chesapeake Energy

Numbers presented are based on waters of relatively high salinity and moderate hardness.

- **Relative economic feasibility.** Circumstances in specific regions may affect economic feasibility. Typically, oil and gas operations have low costs to source and dispose of water relative to the treatment and transportation costs that may be involved with advanced treatment and other logistics for reuse outside oil and gas operations. This was one of the major conclusions of Oklahoma's produced water study.[201] In eastern Pennsylvania, where there are few if any disposal wells and trucking costs hundreds of miles to Ohio are significant, economics supported investment in NPDES and centralized treatment for discharge. Another significant factor can be if a certain produced water is substantially lower in dissolved solids, which could greatly reduce the treatment cost. This example can be seen playing out in California's Kern River oilfield through treatment for agriculture, although treatment cost is not the only consideration and studies regarding food-safety are ongoing. These atypical examples will likely be a guide to future locations where the economics of reuse outside oil and gas operations will be considered on a case-by-case basis.

Other Environmental Considerations

In addition to health or ecosystem impacts that may be associated with reuse scenarios, additional environmental considerations may influence big-picture decision-making on reuse options. These may include emissions from treatment technologies, managing waste materials from treatment, cumulative ecosystem impacts, endangered and threatened species considerations, or other specific or localized issues for an end use such as erosion or flow.

Benefits

In any analysis of risks, benefits should be accounted for as well. Assessment of benefits is particularly important where high costs or potentially significant risks are under consideration. In most scenarios, benefits related to water quantity will be a primary driver for investigating treated produced water reuse alternatives. For example, where water can be treated for surface water discharges, there may be benefits for water users both upstream and downstream due to increased volume in a stream or river. For industrial applications, where fresh water is traditionally used, use of treated produced water can displace fresh water use in the local region, leaving greater volumes available for other users. There may also be scenarios where ecosystem or habitat restoration may be a positive outcome. In addition, the treatment and reuse of produced water may reduce seismicity or pressure issues associated with underground injection and disposal. However, further work is needed to better determine how such benefits should be valued. There may also be benefits from extraction and recovery of various salts and minerals of value in produced water. Reuse also may support the ongoing viability of regional oil and gas operations at times when produced water volumes exceed available disposal capacities or other management options in the region.

201 Report of the Oklahoma Produced Water Working Group (April 2017), http://www.owrb.ok.gov/2060/pwwg.php.

Treatment Technologies

This section provides a general overview of treatment technologies that may be necessary and beneficial for treating produced water for reuse purposes outside oil and gas operations.

Treatment of produced water is critical in achieving defined quality objectives for reuse. The interest in developing and testing various technologies for the treatment of produced water spans the academic, government, and industrial spaces. Produced water treatment presents unique challenges. It can contain TDS levels 5-10X that of seawater (~30,000 mg/L), have significant variability over time and geography, and contain potentially harmful and difficult to treat organic constituents and naturally occurring radioactive materials – all of which makes both treating the water and handling of the residuals a challenge.

TDS are a key consideration in selecting an appropriate treatment train because the presence of high TDS levels can, among other things, negatively impact the efficacy of a technology and greatly influence cost. Treatment challenges associated with TDS impact numerous established treatment processes from biological systems to membrane technologies. For example, in biological systems, high TDS levels impact the microbes used to traditionally remove dissolved organic carbon (DOC), prevent floc formation, and can simply halt non-halotolerant microbes completely.[202] The cost, energy, and technological requirements for TDS removal can present a major challenge for produced water treatment. High levels of TDS not only prevent the use of conventional membrane processes, such as reverse osmosis (RO), but can also create significant solids management issues, even if water can be recovered utilizing select treatment technologies (i.e., thermal distillation). These examples illustrate the challenges associated with TDS from pre-treatment to the final management of residuals, demonstrating why TDS treatment and management are one of the main considerations for any produced water treatment.

Figure 3-12 below includes TDS as a primary axis in the overview of available technologies. The second axis focuses on removal capabilities for other constituents of potential concern.

Other constituents in produced water — including suspended solids, DOC, radionuclides, and metals — are challenging to remove on their own, with some becoming even harder to remove in the presence of high TDS levels. Their removal can be evaluated based on their size, particularly for membrane-based processes, as illustrated in Figure 3-12. Of these various constituents, some may be present as large particles, like suspended solids (>~1 μm), or as small dissolved particles like aqueous salts (< 0.001 μm). Suspended solids (commonly TSS, or total suspended solids) are considered the largest inorganic constituents in produced water, and most treatment methods for suspended solids removal are not impacted by TDS (see Appendix 3-E). DOC can range in size from large humic substances (~ 0.1 μm) to low molecular weight acids or hydrocarbons (~0.001 μm). Unlike suspended solids, DOC removal with biological processes is significantly impacted by high TDS. Metals are small (<0.001 μm) and their removal can also be impacted by TDS, as select treatment processes utilize biological processes (packed bed biofilm reactor). Classic precipitation methods that rely on pH adjustments, can also be hindered by levels of alkalinity or hardness present, by requiring significant amounts of acid or base to adjust the pH to the appropriate levels. Radionuclides (or NORM), like metals, are also small, and present a unique challenge for produced water treatment. This is primarily due to NORM's expected presence in treatment residuals that can significantly increase the cost of waste management and disposal.

An additional treatment consideration not covered in detail below is temperature. The assumption is that produced water will be treated at ambient temperatures. In some cases, depending upon the scenario, temperature can be a challenge because produced water temperatures are elevated when produced and after separation from oil and gas, which can detrimentally impact membrane treatment and biological processes.

202 Benay Akyon, Elyse Stachler, Na Wei, and Kyle Bibby, "Microbial Mats as a Biological Treatment Approach for Saline Wastewaters: The Case of Produced Water from Hydraulic Fracturing." Environmental Science & Technology 49 (10): 6172–80 (2015), https://doi.org/10.1021/es505142t. Also, Ali Reza Pendashteh, Luqman Chuah Abdullah, A. Fakhru'l-Razi, Sayed Siavash Madaeni, Zurina Zainal Abidin, and Dayang Radiah Awang Biak, "Evaluation of Membrane Bioreactor for Hypersaline Oily Wastewater Treatment," Process Safety and Environmental Protection 90 (1): 45–55 (2012), https://doi.org/10.1016/j.psep.2011.07.006.

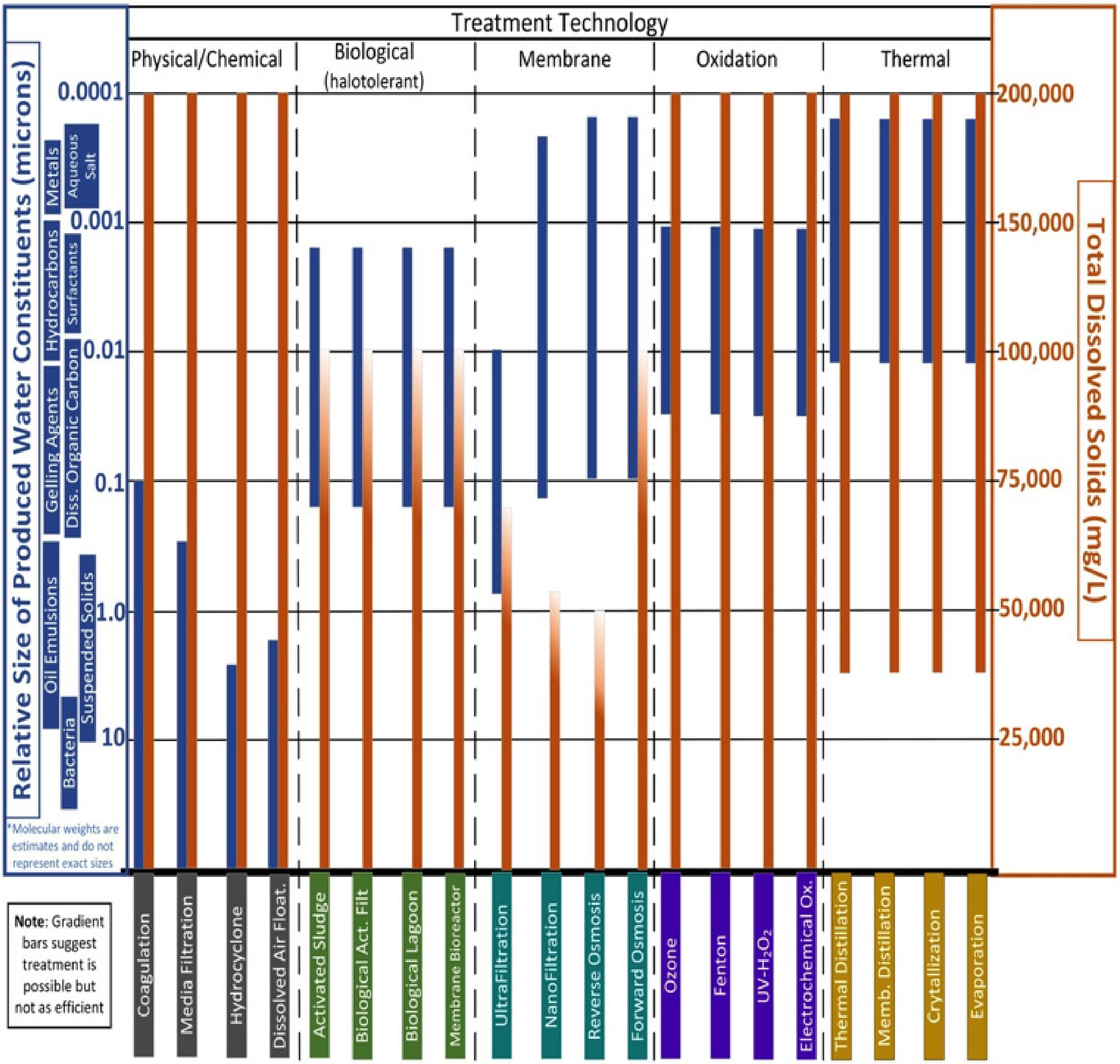


Figure 3-12: Visual Representation of Treatment Technologies and their Average Capabilities for Removing Produced Water Constituents

This visual represents the average capabilities of treatment technologies to remove produced water constituents. It presents a selection of treatment technologies and is not comprehensive. The citations that support this figure are presented in Appendix 3-E.

Produced Water Treatment Challenges: Key Classes of Constituents

The following section describes several key classes of constituents in produced water that may present challenges for treatment to qualities necessary for reuse options outside oil and gas operations.

A substantive table reviewing current treatment technologies and known removal of constituent classes is shown in Appendix 3-E. The table includes information on each technology's current validation status; TDS range; removal capabilities for solids, organics, metals, and TDS; water and waste recovery; energy demand; and associated citations and references.

- **Suspended solids** in produced water consist of small solid particles, that are not dissolved, and remain in suspension. Produced waters can contain high levels of suspended particles and, a variety of technologies are applied for their removal.[203] The most common is basic filtration, though there are other more advanced options. For example, dissolved air flotation is a treatment technology using fine gas bubbles to separate small, suspended particles that are difficult to separate through settling. Another example is coagulation/flocculation, which typically relies on metal salts to coagulate particles into larger solids that can be settled or filtered. These along with a handful of other technologies can and have been used for the removal of suspended solids in produced water treatment. However, the removal of suspended solids in produced water can still present challenges, with the coagulant/flocculant doses needed for suspended solids removal varying greatly from water to water, even for the same basin.[204]
- **NORM** can be a treatment challenge with the settled solids presenting an additional management consideration, especially in the event of a large-scale reuse facility that may generate tons of NORM containing solids. Therefore, while various technologies can be used for NORM removal in produced water, further optimization and analysis is needed in order to more effectively consider management of the NORM in treatment train design. The level of NORM in produced waters varies greatly by geography and formation. NORM should be a primary consideration in the treatment technologies considered.
- **Dissolved organic constituents (DOC)** are ubiquitous in water and have various sources. For produced water, these sources are the natural organic matter found in the makeup water, the organic chemicals present from the fracturing fluid mixture (i.e., friction reducers), organic constituents from the formation (i.e., hydrocarbons), and chemicals that form during subsurface reactions between these three main sources.[205] There are various treatment technologies aimed at removing this DOC, such as activated sludge process or biologically activated filtration, which rely on microorganisms to remove DOC. The TDS levels in produced water present challenges for these microbial based treatments, since elevated levels of TDS are known to impact even the degradation of carbohydrates. Biological treatments have been demonstrated at TDS levels greater than 100,000 mg/L, but these were from other industries (i.e., pickling or tanning wastewater) or synthetic waters, and had long hydraulic retention times (> 100 hrs.).[206] Additionally, produced waters may contain specific organic constituents in

203 Yaal Lester, Imma Ferrer, E. Michael Thurman, Kurban A. Sitterley, Julie A. Korak, George Aiken, and Karl G. Linden, "Characterization of Hydraulic Fracturing Flowback Water in Colorado: Implications for Water Treatment," *Science of the Total Environment* 512–513 (April 2015): 637–44, https://doi.org/10.1016/j.scitotenv.2015.01.043.

204 See, e.g., James S. Rosenblum, Kurban A. Sitterley, E. Michael Thurman, Imma Ferrer, and Karl G. Linden, "Hydraulic Fracturing Wastewater Treatment by Coagulation-Adsorption for Removal of Organic Compounds and Turbidity," *Journal of Environmental Chemical Engineering* 4 (2): 1978–84 (2016), https://doi.org/10.1016/j.jece.2016.03.013.

205 Kathrin Hoelzer, Andrew J. Sumner, Osman Karatum, Robert K. Nelson, Brian D. Drollette, Megan P. O'Connor, Emma L. D'Ambro, et al., "Indications of Transformation Products from Hydraulic Fracturing Additives in Shale-Gas Wastewater," *Environmental Science & Technology* 50 (15):8036–48 (2016), https://doi.org/10.1021/acs.est.6b00430.

206 Olivier Lefebvre and René Moletta, "Treatment of Organic Pollution in Industrial Saline Wastewater: A Literature Review," *Water Research* 40 (20):3671–82 (2006), https://doi.org/10.1016/j.watres.2006.08.027.

the DOC, like biocides or phenols that are inhibitory to microorganisms.[207] Membranes, such as ultrafiltration, nanofiltration, and reverse osmosis can also be used for the removal of DOC. However, they will require significant pre-treatment to protect the membranes from fouling and are also impacted by the TDS levels; since TDS levels greater than 50,000 mg/L are typically inhibitory, due to the pressures required and low water recovery levels.[208]

Because treatment system efficacy is highly dependent on the type, concentration, and behavior of DOC, which can be variable in produced waters, and thorough piloting of treatment systems is highly recommended. For example, pH variability during treatment can cause the precipitation of DOC, causing significant fouling of treatment systems. Other treatment technologies, such as thermal distillation, can handle DOC and produce a high-quality distillate however DOC will be concentrated in the blowdown or waste stream from this process unless there is a thermal destruction aspect of the treatment. Technology selection will be dependent and vary by location, as well as residuals management needs; particularly for membrane-based processes.

- **TDS** is the total of organic and inorganic constituents dissolved in a given water. In produced waters TDS is dominated by sodium and chloride, but can include various metals, hardness, and alkalinity to list a few. Many treatment processes do very little for these dissolved solids, which can be the most challenging and expensive constituent to remove in produced water. Removal of TDS is being demonstrated around the globe with seawater desalination, but levels of TDS in produced water are generally higher, with many basins having average TDS content ranging up to several times that of seawater (see Figure 3-13). Technologies aimed at addressing TDS for waters greater than 50,000 mg/L currently include primarily membrane distillation, thermal distillation, and crystallization. The challenges associated with these technologies are many, but primary considerations include associated costs and the need to manage significant amounts of salts and/or concentrated solids that may be contaminated with constituents of concern removed in treatment.

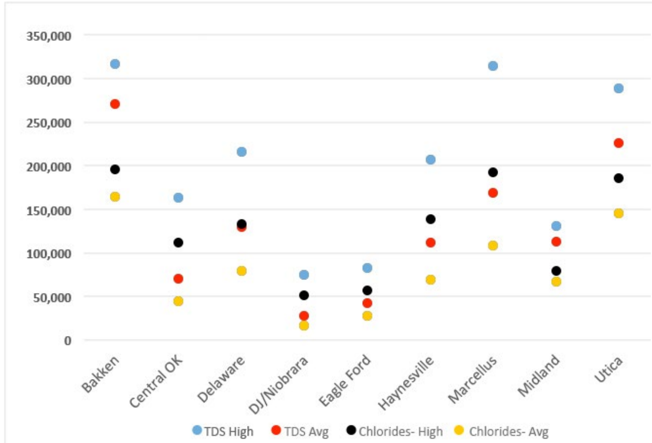


Figure 3-13: Water Quality by Basin (TDS and Chlorides)
Source: 18 Producing Companies (from Module 2, Figure 2-61)

Figures on Y axis represent Mg/L. Many basins have average TDS content ranging up to several times that of seawater.

The challenges and costs involved in the design and use of treatment systems necessary to meet reuse quality objectives are primary considerations in any reuse scenario and must be investigated early in the decision process.

A substantive table reviewing current treatment technologies and known removal of constituent classes is shown in Appendix 3-E.

207 Molly C. McLaughlin, Thomas Borch, and Jens Blotevogel, "Spills of Hydraulic Fracturing Chemicals on Agricultural Topsoil: Biodegradation, Sorption, and Co-Contaminant Interactions," *Environmental Science & Technology* 50 (11):6071–78 (2016) https://doi.org/10.1021/acs.est.6b00240.

208 Katie L. Guerra, Katharine G. Dahm, and S. Dundorf, "Oil and Gas Produced Water Management and Beneficial Use in the Western United States." (Denver, CO: U.S. Department of the Interior, Bureau of Reclamation, 2011), https://protect-us.mimecast.com/s/kJC6C73A0xh4OlQI8P5wWi?domain=usbr.gov.

Theoretical Treatment Trains

When evaluating treatment technologies, it is critical to understand treatment goals, particularly how technologies are used together in "treatment trains" and the capabilities of these systems. A treatment train is often needed to address the many types of constituents in produced water, and will include multiple steps to remove various constituents, in a strategically designed stepwise fashion. Each step in the treatment train will be considered for its ability to remove the specific constituent or class of constituents and manage its resulting residual solids or sludges, which could be substantial. The treatment train needed for any given reuse scenario could look significantly different from others based on the produced water and the water treatment goals. Each technology has its own pros, cons, and purposes.

Figures 3-14 to 3-17 depict theoretical treatment trains for select produced waters. The authors have included these as theoretical options to illustrate that several steps are needed to treat produced water and that treatment combinations vary depending upon produced water character and quality objectives. Numerous potential combinations are possible and it is likely that additional steps may be required. Although residuals management is not fully considered here (i.e., suspended solids removal), it is a vital component of design.

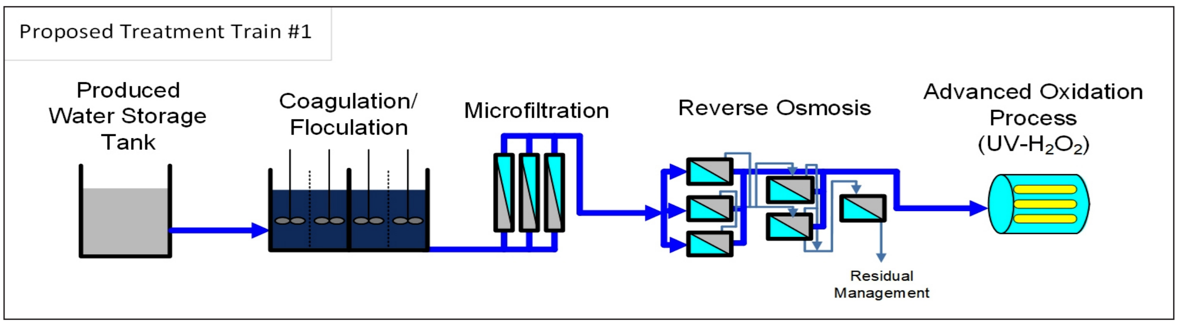


Figure 3-14: Low-TDS Treatment Train #1 (<40,000 mg/L TDS)

In the first step, coagulation/flocculation removes suspended solids and hardness in the produced water. In the second step, microfiltration removes additional suspended solids and large organic constituents. In the third step, reverse osmosis targets dissolved constituents, both organic and inorganic (i.e., TDS and DOC). In the final step, advanced oxidation targets oxidizable organic constituents.

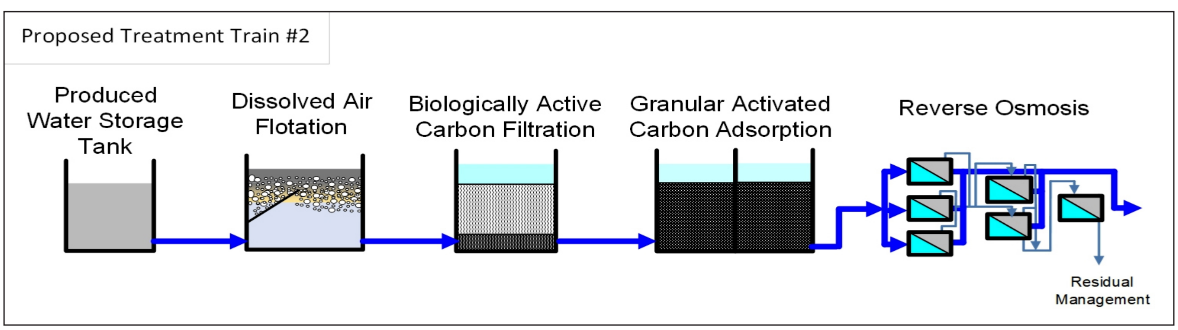


Figure 3-15: Low-TDS Treatment Train #2 (<40,000 mg/L TDS)

This variation leads with dissolved air flotation to remove suspended solids. The second step is a biologically active filtration step to reduce both suspended solids and dissolved organics. The next step is granular activated carbon to target dissolved organics and some remaining suspended solids. The final step is nanofiltration to address both dissolved organics and total dissolved solids.

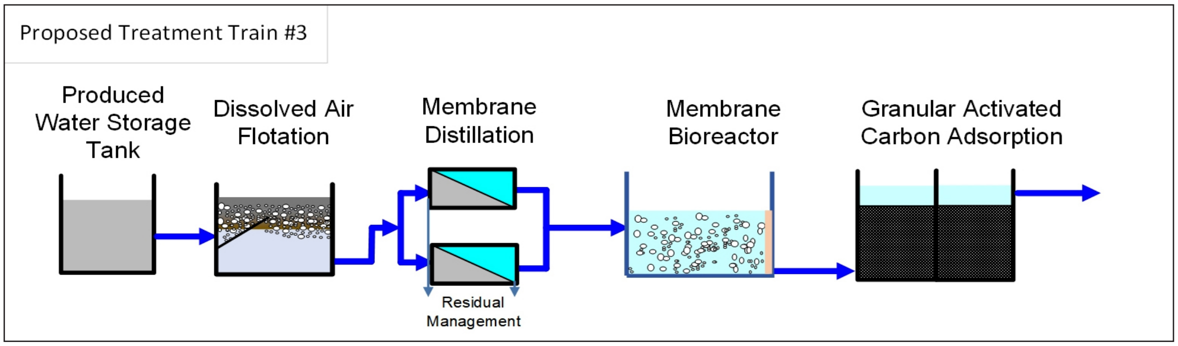


Figure 3-16: Medium/High-TDS Treatment Train #3 (75,000 ~ 150,000 mg/L TDS)

This train again leads with dissolved air flotation to remove suspended solids. The second step is membrane distillation (MD) for the removal of TDS, both dissolved organics and inorganics. The third step is a membrane bioreactor targeting the dissolved organic carbon that came through the MD. The final step is granular activated carbon for additional organic constituents' removal.

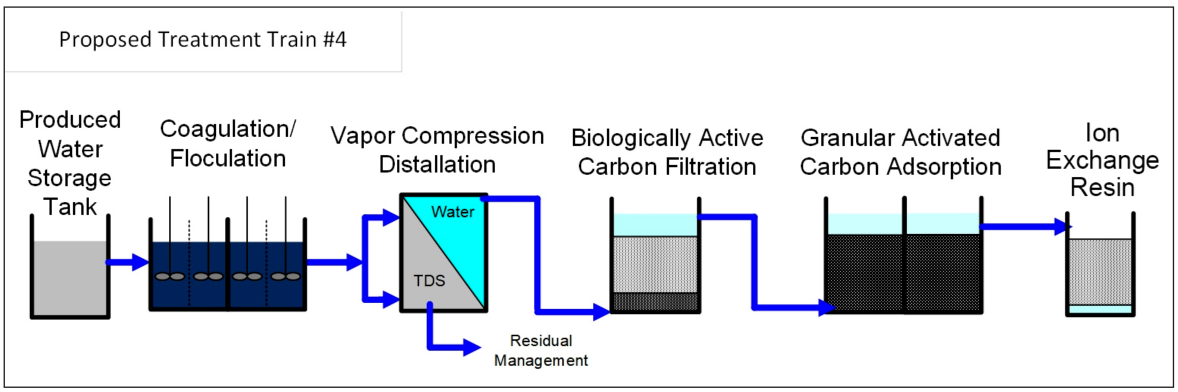


Figure 3-17: High-TDS Treatment Train #4 (>100,000 mg/L TDS)

This train begins with a coagulation/flocculation step to remove suspended solids. The second step is vapor compression distillation to remove TDS, both dissolved organics and inorganics. The third step is a biologically active filtration to remove remaining dissolved organics. The fourth step is granular activated carbon, targeting additional dissolved organics removal. The final step is ion exchange, targeting very specific constituents present in the treated produced water.

Treatment Technology: Research Recommendations

The treatment of produced water presents a unique challenge and opportunity for the oil and gas industry, researchers, and regulators alike. Considerable unknowns regarding the precise chemical character of produced water can impact the design and evaluation of treatment trains for various reuse scenarios. Furthermore, water quality variation from location to location, means that there is no single solution or "silver bullet" for produced water. It is likely that each basin, and perhaps even sub-basins or specific operational practices, will require a thorough investigation on best practices and technologies available for treating their produced water and the outcome of this investigation is likely to change depending on end use.

The following research considerations could be addressed by operating companies, academic institutions, government research groups, or collaborative partnerships. Scenario-specific research and development may include more targeted objectives not mentioned here.

1. Expand data development and publication of the efficacies and capabilities of different treatment scenarios for different produced waters;
2. Conduct desk-top/bench-scale or pilot-scale treatment demonstrations of non-synthetic produced water sampled from a variety of geographies and time scales;

3. Identify strategically engineered treatment trains able to manage removal of constituents of concern to necessary levels while producing manageable residual streams;
4. Conduct realistic, field-scale piloting of individual treatment technologies and treatment trains to assess response to expected changing variables, flow rates, produced water quality, upsets, etc.;
5. Further investigate technologies/methods that can recover valuable resources from produced water that may offset treatment cost;
6. Develop strategies to manage treatment residuals, taking into account waste characterization and disposal, the potential for recycling, reuse or sale, and storage and transportation;
7. Identify indicator constituents or classes of constituents to help assess the treatment of produced water and consider the parallel use of whole effluent analytical methodologies to flag pass-through of constituents of concern; and
8. Expand analysis of factors unrelated to effluent quality outcomes, such as energy requirements, emissions, footprint, and infrastructure.

State of the Science: Literature Review

Research conducted in areas relevant to this module has significantly increased in recent years. GWPC worked with collaborating experts to conduct a literature review with a goal to cast a relatively broad net and gather references and resources that may be useful to this discussion moving forward. For example, the literature review included studies related to "degraded water" reuse, which is the reuse of mostly fresh waters that have been contaminated in some way through their initial use for things like industrial processes, household effluents, or runoff. While these waters may differ from produced water in their character and origin, this subject was included in order to provide a more complete assessment of literature around the concept of treatment and reuse of waters that may be more traditionally considered a waste. Learning from the process and findings of research in this somewhat analogous area can inform produced water reuse assessment, research, and decision-making. Similarly, many of the existing peer-reviewed studies that directly address produced water analyze the produced water prior to treatment or consider chemicals utilized in hydraulic fracturing fluids.

The search logic and process for identification, review, and evaluation of the literature is described with more depth in Appendix 3-F.

Rather than simply provide references and citations, the summaries that follow present a cursory overview of the "state of the science" in the four topics covered in the review: (1) degraded water reuse, (2) produced water quality, (3) produced water reuse for non-oil and gas purposes, and (4) environmental and human health hazards and potential risks from produced water reuse. A bibliography organized by topic is available in Appendix 3-G. The following sections provide an overview of each topic and a summary of where, how, and why research was conducted along with generalizations about findings. The overviews do not substantively present the findings of all papers covered by the literature review and does not address other relevant topics or issues of concern such as policy or regulation unless directly relevant to the literature reviewed.

Note to readers: this is only one discrete literature review effort. It does not include all possible papers, subjects, and references that may be relevant to produced water. In fact, informative studies on a variety of topics or reuse scenarios are likely not represented here. Where projects are proposed or proceed, conducting a more targeted literature review may be a useful component of initial assessment of that effort.

Degraded Water Reuse

Background

Rising water supply demands worldwide have contributed to increased interest in the intentional reuse of degraded waters. Degraded water, typically fresh water that has been subjected to chemical, physical, or microbiological degradation, can provide various opportunities through reuse. Research on the use of degraded water has primarily focused on: industrial wastewater effluent; municipal wastewater effluent; graywater (wastewater without fecal contamination), irrigation/livestock runoff; and, stormwater runoff (O'Connor et al. 2008). While the papers covered here are not specific to produced water reuse itself, the process and concepts considered for reuse of other degraded waters, such as municipal wastewater, can be informative.

Reuse options can be divided into non-potable, indirect potable, and direct potable reuse. Non-potable reuse options include reuse in agriculture (i.e., crop irrigation, livestock watering), industrial (e.g., cooling tower blowdown, road-spreading/dust suppression), and urban reuse (e.g., golf courses, highway medians). Indirect potable reuse of degraded water may include surface water augmentation and groundwater recharge. These "indirect" methods typically involve careful planning with safeguards in place to protect human and ecological receptors and rely on mixing, dilution, biological buffering mechanisms (such as nitrite and ammonia assimilation by plants) or engineered buffers to provide multiple layers of protection in the environment (Metcalf and Eddy 2007, O'Connor et al. 2008). Direct potable reuse (DPR) is similar to indirect potable reuse (IPR), however, unlike IPR there are no environmental barriers in DPR and therefore advanced treatment systems are needed (EPA 2017). As of 2017, Texas and New Mexico were the only states with planned or implemented DPR systems (EPA 2017).

Some effort has been made to aggregate water quality guidelines for reuse, though this work has not been exhaustive. Pham et al. (2011) compiled water reuse guidelines from international sources as a "decision-analysis screening tool" that may be useful to assess reuse for irrigation, livestock, aquaculture, and drinking water. The study identified guideline values for at least one reuse option for over 50 water quality parameters (Pham et al. 2011). While an increasing number of regulatory programs surround non-potable reuse like graywater systems,[209] specific regulations for indirect and direct potable reuse are less common. Some states like California, Arizona, Florida, Oklahoma and Texas have policies or programs that support or encourage various degraded water reuses and, some states are working toward development of programs and regulations for other reuse options.[210] Beyond this high-level overview, specifics of regulatory programs are not commonly included in peer-reviewed literature, a few citations on this point are included here as footnotes. Where an operator, state, municipality or other group is interested in a specific reuse program, investigation of the regulatory systems surrounding various types of degraded water reuse should be conducted in addition to a search of the peer-reviewed literature.

Potential human health risks

Adverse health risks from water reuse can result from both direct and indirect exposure to contaminants. Health risks due to microbial organisms have been addressed the most frequently (Weber et al. 2005) and were the primary human risk factor mentioned in many of the reviewed papers on degraded water reuse (Hamilton et al. 2006; Hamilton et al. 2007; Hyland et al. 2015). Microbial pathogen exposure from contact with human or animals waste could occur when reclaimed water from livestock water or municipal waste water is not effectively treated prior to reuse. When used for irrigation, known contaminants of concern in degraded water may enter the human food chain if they accumulate in edible crops. Potential health risks due to the uptake of emerging chemicals of concern such as pharmaceuticals, endocrine disrupting chemicals or EDCs, and other emerging contaminants of concern (ECOC) have not been as thoroughly addressed and were not routinely discussed in published review papers on water reuse (Bikerton et al. 2011; Anderson et al. 2013). Li et al. (2013) evaluated the occurrence and concentrations of EDCs in aquifers recharged with reclaimed municipal wastewater. Results show that EDC concentrations decreased with greater aquifer depth but increased when reclaimed wastewater was continuously discharged during the dry season. Blaine et al. (2014) found that perfluoroalkyl acids (PFAAs), which are persistent organic contaminants, bioaccumulated in the edible portion of strawberries and lettuce. A recent review by the NRC (2012) suggests that the number of potential chemicals in reclaimed municipal wastewater is in the thousands, indicating that monitoring requirements should be more robust and comprehensive than those used currently.

209 See, e.g., 30 TX. Admin. Code §210.81 – 210.85 (Texas Commission on Environmental Quality - Use of graywater and alternative onsite water (effective Dec. 20, 2016)); Ariz. Admin. Code § 18-9-7 (Arizona Department of Environmental Quality – Use of recycled water (effective Jan 1. 2018)).

210 *State Policy and Regulations*, WateReuse.org, https://watereuse.org/advocacy/state-policy-and-regulations/.

Potential ecological risks

Ecological risks of degraded water reuse are based on the quality of the water at the time of release. Treated wastewater effluents are regularly discharged into waterbodies via a point-source discharge after undergoing secondary or even tertiary treatment (NRC 2012). Although these discharges are subject to multiple layers of treatment before discharge, and generally involve permits with applicable discharge limits, they may still contain a mixture of organic and inorganic chemicals that may cause unanticipated adverse effects in the receiving environment. Other ecological impacts may include a change in pH, dissolved oxygen, temperature, nutrient loading (phosphorus, nitrogen), and increased total dissolved solids (TDS), and total suspended solids (TSS) (Soucek et al. 2011).

Ecological impacts from non-point source runoff is also a concern when water reuse involves the application of a degraded water to land, such as with crop irrigation. O'Conner et al. (2008) note that approximately 29% of the total volume of irrigation water returns as irrigation return flow. Therefore, any contaminants of concern may leave the application site as run-off and enter surface waters.

Direct application of reused water to land must also account for the potential for increased soil sodicity, or an increase in sodium held by the soil. Some recycled water, high in dissolved salts, may increase the salinity in the soil to levels that are unacceptable by either native vegetation or planted crops. Further, Hyland et al. (2015) suggests water reuse evaluation studies are not effectively evaluating plants as many of these studies have included hydroponic test exposures and therefore, do not account for soil-root/plant interaction. Many additional papers are included in the bibliography, including a large body of agricultural literature on sodium adsorption ratios, etc. that may be useful to consider with respect to produced water.

Understanding risk of degraded water reuse

Degraded water reclamation and reuse research includes reclaimed water from a variety of sources. Several studies emphasized the need to develop a consistent risk assessment framework to evaluate degraded water in the context of potential reuse scenarios, similar to the discussion of produced water in this Module. For example, FitWater, (Chhipi-Shrestha 2017) provides a decision support tool (DST) for evaluating degraded waters in the context of the reuse scenario in question. A final ranking score allows risk managers to then make the best decision regarding reuse options based on several criteria including: the amount of degraded water to be reused, the cost of treatment, potential health risks (based on microbial risk assessment, particularly with surface water reuse scenarios), energy use, and carbon emissions. The ranking/scoring system provides a straightforward conclusion allowing risk managers to either move forward with a specific reuse or treatment option. Chen et al. (2013) proposed a Full Assessment procedure for use in Sydney, Australia to evaluate reuse options based on technical, economic, and social principles to implement a preferred reuse. Although similar in that the tool provides a final score, this tool was unique in that it also included a social impacts evaluation.

The literature included in this review provides useful suggestions for the development DSTs and a risk assessment framework that can be used to implement a method by which water reuse scenarios can be consistently evaluated. However, risk assessment strategies evaluated in these publications do not thoroughly consider potential human health risks or ecological consequences from chemical exposure. One major gap in both human and ecological risk assessments is the mixture toxicity of various chemicals found in wastewater (NRC 2012). Although the toxicity of chemicals with similar modes of action can be predicted using the sum of the toxicity of the individual components (e.g., PAHS, DiToro et al. 2007), it is far more difficult to predict toxicity when modes of action are different (NRC 2012). Further, the long-term impacts from exposure to chemical mixtures is not understood and may require additional testing to validate model predictions. As outlined by the NRC (2012), additional understanding of contaminant attenuation, environmental buffers, and potential chemical transformation and byproducts due to treatment or biological and abiotic interactions are important in the development of appropriate treatment and reuse options. Although this review did not directly assess the impacts of irrigation run-off (irrigation return flow) to human and ecological health, this pathway must be considered when sources of irrigation of water are considered. Research needs such as this parallel some of the considerations provided in this module and may be relevant to produced water reuse assessment.

Produced Water Quality

Produced water is the largest waste stream associated with oil and gas extraction; it has a highly variable composition that can depend upon the geology of the field, the type of hydrocarbon being developed, and the age of the well (Fakhru'l Razi et al. 2009). While the major compounds of produced water are generally consistent, the concentration of the constituents can vary by orders of magnitude (Wesolowski et al. 1987, Igunnu and Chen 2017).

In general, produced water is a complex mixture of inorganic and organic constituents such as dissolved and dispersed petroleum hydrocarbons including polycyclic aromatic hydrocarbons, geogenic minerals associated with the formation including NORM, heavy metals, monovalent/divalent/multivalent elements and salts, and added production and maintenance chemicals and their transformation compounds (Alley et al. 2011, Oetjen et al. 2017, 2018, Hoelzer et al. 2016). According to the USGS Geochemical Database, the total dissolved solids (TDS) of produced water ranges from fresh (less than 500 mg/L) to hypersaline (greater than 500,000 mg/L, Blondes et al. 2017).

Early studies and federal databases

In their 1987 report prepared for the Gas Research Institute, Wesolowski et al. note that for produced water, "[d]etailed chemical analyses and quantitative summaries of treatment and disposal practices were severely lacking." That early study sought to increase understanding of produced water by collecting and analyzing seventeen samples of produced water from sixteen natural gas production sites. The team used methods and parameters defined previously in a study conducted by EPA (Wesolowski et al. 1987). A summary of this study as well as data generated by studies conducted by EPA and the American Petroleum Industry (API) can be found in Fillo et al. (1992); however, these studies limited their characterization to conventional water quality parameters, minor and trace metals, volatile and semi-volatile organic compounds, and RCRA criteria.

Currently, two federal sources of data are available on oil and gas wastewater: the U.S. Geological Survey (USGS) National Produced Waters Geochemical Database and the Hydraulic Fracturing for Oil and Gas: Impacts from the Hydraulic Fracturing Water Cycle on Drinking Water Resources (US EPA 2016). The USGS Geochemical Database was recently updated (v2.3, 2017) and is currently a compilation of 40 databases, publications, or reports, though it is continually growing (Blondes et al. 2017). While the original database focused on major elements only (e.g., TDS, sodium, calcium, and chloride), the new database has been expanded to include trace elements, isotopic data, and time-series studies of produced water changes. This database includes data from conventional and unconventional oil and gas developments as well as geothermal wells. However, the database is limited with respect to organic compounds. For example, not including geothermal, injection well, or undefined well data, of the 113,374 samples in the database, less than 2% have limited organic chemical data. Furthermore, many entries are missing basic data, such as location (10% lack data), sample date (26% lack data), and the depth of the well or sample (29% lack data). For those that have sample dates, 90% were sampled prior to 2000.

The second database is presented in Appendix H to the Final Report of the EPA's Assessment on Hydraulic Fracturing on Drinking Water Sources (2016), which reports on the chemicals identified in fracturing fluid, flowback, and produced water, but without any corresponding concentration data.[211] The appendix contains 1,606 chemicals that were reported to be used in hydraulic fracturing fluids or detected in produced water of hydraulically fractured wells. Additionally, this study identified 131 chemicals that have been detected in produced water that do not have an associated CAS number, and therefore were not included in the following analysis. The reported chemicals used downhole are from 2005–2013 and total 1,084 unique compounds; there were 599 chemicals found in literature on oil and gas wastewater, 77 of which were also reported to be in hydraulic fracturing fluid as identified in 28 sources. These sources are listed in the appendix and included both peer-reviewed literature and industry or state-based

211 Appendix H can be downloaded alongside other useful appendices from the EPA Hydraulic Fracturing study at www.epa.gov/hfstudy. Appendix H contains more than 100 pages and was therefore not included as an attachment to this report.

research including the New York State Department of Environmental Conservation (NYSDEC, 2011), Geological Survey of Alabama (2014), the Pennsylvania Department of Environmental Protection (PADEP, 2015), industry self-reporting, and a study conducted for the Marcellus Shale Coalition member companies by the Gas Technology Institute (GTI, Hayes 2009).

However, EPA notes that this database for "… flowback and produced water chemicals identified… is almost certainly incomplete" (Ch 9. EPA, 2016). The EPA indicates that the relatively small number of studies, combined with a lack of comprehensive analytical methodologies, as well as complex matrix interference rendering standard methods inappropriate, have resulted in chemicals being undetected. Importantly, the report concludes that "… standard analytical methods are not adequate for detecting and quantifying the numerous organic chemicals, both naturally occurring and anthropogenic, that are now known to occur in produced water" (Ch 7, EPA 2016).

A third and up-to-date resource is the FracFocus chemical registry that includes disclosures of chemicals used in hydraulic fracturing.[212] This database is publicly available and can be downloaded to evaluate chemical use patterns in specific development areas and may also be useful in identifying potential constituents of concern.

Non-standard analytical methods (research methods)

In their assessment of emerging technologies and analytical methods for use in produced water, Oetjen et al. discuss the hurdles in characterizing oil and gas wastewater including the suitability of analytical methods in hypersaline water and the lack of methods for many suspected chemicals in produced water (2017). As another example of analytical challenges, Nelson et al. demonstrate that the complex matrix common to produced water interfered with EPA standard methods to measure NORM, reducing the recovery of radium-226 to 1 percent of its total (2014).

To meet these chemical characterization challenges, method validation along with a combination of target, suspect, and non-targeted analytical methods are needed (Oetjen et al. 2017). To this end, a number of research groups have demonstrated the efficacy of sample preparation techniques to remove or reduce matrix effects combined with non-targeted screening or high-resolution mass spectrometry (HRMS) methods to identify previously unknown compounds in produced water (Hoelzer et al. 2016, Khan et al. 2016, Luek and Gonsior 2017, Luek et al. 2017, 2018, Maguire-Boyle and Barron, 2014, Nell and Helbling 2018, Piotrowski et al. 2018a, 2018b, Rosenblum et al. 2017, Thurman et al. 2014, 2017). Additionally, Thacker et al. developed a number of analytical methods to characterize oil and gas wastewater from West Texas unconventional developments, which they used to identify a number of chemicals that are commonly reported as hydraulic fracturing fluid components, including 2-butoxyethanol, cocamide diethanolamines, and o-xylene (2015).

Hoelzer et al. (2016) analyzed flowback and produced water from six Fayetteville Shale wastewater samples using advanced non-targeted gas chromatographic analytical techniques. The research team were able to identify approximately 400 organic chemicals and attempted to categorize the source of the chemicals as likely geogenic, disclosed production chemicals, or likely anthropogenic. The researchers also identified several suspected transformation products or undisclosed compounds. Those compounds included halogenated compounds, which, due to low disclosure frequency, are likely unintended transformation products. Halogenated organic compounds are concerning due to their likelihood to be persistent organic pollutants.

Thurman et al. identified polyethylene glycol surfactants (PEGs), polypropylene glycol surfactants, and linear alkyl ethoxylates (LAEs) using high-resolution liquid chromatography (2014, 2016). Using the same methodology, Ferrer and Thurman were able to identify and elucidate the chemical structures of the biocides alkyl dimethyl benzyl ammonium chloride (ADBAC) and glutaraldehyde, and cocamidopropyl surfactants (2015). The authors found that ADBAC was present in 54% of samples collected from flowback and produced waters in Weld County, CO.

Khan *et al* (2016) analyzed produced water from the Permian basin (shale-oil) from eight wells, using non-targeted methods to look for volatile organic compounds. Samples were collected late enough

212 www.fracfocus.org.

after production that the researchers surmised that they represented native formation water rather than hydraulic fracturing fluid. They were able to confidently identify 327 compounds; primarily known as being from the source oil.

Despite the recent increase in peer-reviewed literature on novel method development and characterization of produced water, Luek and Gonsior found the majority of samples for these studies are not necessarily collected where most oil and gas are being produced and therefore may not be representative of produced water generally (2017). Approximately 70 percent of the studies to characterize organic compounds from hydraulic fracturing fluids and wastewater were conducted with produced water sampled from the Marcellus basin, which only accounts for 37 percent of natural gas production and less than 0.01 percent of oil production (Luek and Gonsior 2017). However, continued development of these methods and their application to greater and more diverse types of produced water is an important first step towards creating robust, standard methods.

Produced Water Reuse for Non-Oil and Gas Purposes

There have been several proposed or implemented strategies for produced water management that seek to capitalize on its value as a water source, though peer-reviewed literature on these reuse scenarios as-applied have been limited to date. Active or hypothesized reuse options include: aquifer storage and recovery (ASR); subsidence control; mitigating salt-water intrusion; agriculture and irrigation uses; industrial uses, such as in power production or tower cooling; dust suppression and road deicing; salt and/or elemental extraction/recovery; and even as potable drinking water (see, e.g., Veil 2011). Studies that have investigated the impacts from these implementations are not common and instead most often focus on the potential for or treatability of produced water for new purposes (see, e.g., Dallbauman and Sirivedhin 2005; Echchelh, Hess, and Sakrabani 2018; Guerra, Dahm, Dundorf 2011; Hagstrom et al. 2016; Horner, Castle, and Rodgers 2011; Martel-Valles et al. 2016; Oetjen et al. 2018b, Sirivedhin and Dallbauman 2004; Xu, Drewes, and Heil 2008). Most of these studies conclude that while possible in select circumstances, most produced water will require high levels of treatment to meet reuse objectives outside oil and gas operations, which is likely to be currently cost-prohibitive.

Where research exists on irrigation with produced water, it has primarily focused on coal bed methane (CBM) produced water due to its availability and often lower-salinity characteristics. (Beleste et al. 2008; Bern et al. 2013; Burkhardt et al. 2015; Ganjegunte, Vance, and King 2005; Ibrahim, Marroff, and Wafi 2009; Johnston, Vance, and Ganjegunte 2008; Mullins and Hajek 1998). Collectively, these studies indicate that direct application of CBM to soil can have deleterious effects on both the plants and the soil, causing leaf-burn and affecting soil infiltration and its structure. However, careful consideration of the types of soil, how the irrigation is applied (i.e. sub-surface irrigation) (Beleste et al. 2009, Bern et al. 2013), and if the plant is salt-tolerant (Rambeau et al. 2004) have led to some successful use of CBM in the short-term. Long-term application exacerbates harmful effects on soil and is not recommended (Burkhard et al. 2015; Ganjegunte, Vance, and King 2005). Jackson and Meyers examined the feasibility of using CBM in hydroponics and aquaculture by growing tomatoes and cultivating tilapia, respectively (2002). Tomatoes grown with CBM were smaller, tasted salty, and had elevated levels of sodium, chloride, arsenic, barium, chromium, lead, selenium, and silver. Tilapia had a 27% mortality rate when grown in produced water versus the control; however, there was some discrepancy in the counting the total number of fishes grown in the control.

Heberger and Donnelly (2015) compiled a table of nine projects where produced water has been used for crop irrigation in California. Studies are on-going regarding food-safety and other considerations regarding this practice as specifically applied in the Central Valley. There have been a handful of greenhouse studies that have been conducted on the use of oil and gas produced water for irrigation of tomatoes (Martel-Valles et al. 2014) and non-food crops including western wheatgrass and alfalfa (Brown et al. 2010), hemp and cotton (Rambeau et al. 2004), and biofuels like switchgrass and rapeseed, which are considered relatively salt-tolerant (Pica et al. 2017). Martel-Valles et al. found that two of the three different produced waters could successfully grow tomatoes, however, they found that the plants had a decreased leaf-weight indicating some detrimental effects on biomass (2014). The third produced water was unsuccessful, which they attributed to elevated levels of petroleum hydrocarbons, copper, and chloride concentrations, despite having comparable TDS levels to the other waters tested. Brown et al. found that produced water had to be treated prior to use for irrigation, and that the type of treatment affected the elemental compositions uptaken by the plants (2010). Pica et al. looked at a variety of dissolved solids and organic carbon concentrations in produced water and found that high salinity, as well as organic content of produced water reduced biomass production and that five inorganic compounds were uptaken by the plants (2017).

Studies that specifically investigate soil implications are limited. Some studies relevant to land application have considered impacts related to soil application as a form of disposal (Al-Haddabi and Ahmed 2007) or as a result of spills (Oetjen et al. 2018a), though context should be given in translating conclusions from these studies to intentional reuse scenarios where treatment is likely to occur. More recently, some researchers have launched efforts to more fully understand potential impacts of produced water on not just crops but also on soil health. For example, a team at Colorado State in Fort Collins is actively investigating potential impacts of the use of treated and diluted produced water for irrigation of wheat crops and associated effects on plant growth as well as accumulation and leaching processes in agricultural soil.[213]

Finally, studies also exist regarding road-spreading for various purposes. Currently, thirteen states allow for road-spreading of produced water (Tasker et al. 2018) either for de-icing or dust-suppression, though some studies have indicated that its use is ineffective for dust-control (Graber et al. 2017). Studies of this reuse option have also found that road-spreading contributes to increased radium in roadways (Tasker et al. 2018), and increased metals concentration in the environment around the application site (Graber et al. 2017) and due to leaching after rain events (Tasker et al. 2018).

Environmental and Human Health Hazards and Potential Risks from Produced Water Reuse[214]

The current state of the "impacts" literature on produced water

Alternative uses of onshore produced water may alleviate one of the predominant waste management issues associated with unconventional and conventional oil and gas production while reintroducing a potentially valuable resource, especially in arid and agricultural regions. However, the risks associated with introducing treated produced water into the environment and resulting environmental, wildlife, and human exposures have not been comprehensively evaluated. This section of the literature review aims to (a) identify scientific reports on environmental and human health impacts of produced water, and (b) define knowledge and gaps in the literature pertaining to chemical contaminants of concern, relevant exposures, and human and environmental health impacts. Details on the scope of this review can be found in Appendix 3-F, which provides an overview of the methodology and search logic. Software-aided evaluation of the search results revealed a strong focus on compositional, exposure and ecotoxicological studies (Figure 3-18 A–D). Currently, approximately equal numbers of articles focus on onshore and offshore produced waters. While offshore produced water is not a part of the Module 3 assessment thus far, literature pertaining to offshore produced water was included in our search. This substantial body of literature is included because produced waters are in many ways expected to be similar in chemical character to produced waters found onshore, recognizing variations that might occur from basin to basin and due to different production practices. Numerous similar concepts can provide insight, such as analytical methodology to quantify contaminants of concern, whole effluent toxicity tests, and the nature of geogenic contaminants associated with hydrocarbon reservoirs. Due to this general similarity, studies of offshore produced water may inform an assessment of onshore produced waters, even though not all information captured may be directly relevant to

213 See, e.g., http://borch.agsci.colostate.edu/group-members/molly-mclaughlin/.

214 GWPC would like to thank ExxonMobil Biomedical Sciences, Inc. for their significant contribution to this portion of the literature review summary and their services in assisting to conduct the review itself. Portions of this section have been presented by ExxonMobil Biomedical Sciences, Inc. in a poster session: F.A. Grimm, K.P. Christensen, K.S. Lavelle, S.I. Maberti, M.S. Alexander, T.F. Parkerton, D.J. Devlin, "Review of Environmental and Human Health Hazards from Alternative Applications of Produced Water," Poster Presented at the National Academies of Science Workshop on Strategies and Tools for Conducting Systematic Reviews of Mechanistic Data to Support Chemical Assessments, December 10-12, 2018, Washington, DC.

onshore produced water management. Additionally, more historical information and data are available on offshore produced water management due to different operational realities and regulatory requirements for management, including discharge. For these reasons, the summary below does not, in every case, explicitly identify a study as onshore or offshore, however the cited papers reviewed for this section can be referenced for detail if necessary. Furthermore, temporal publication trends reveal a proportionally much stronger recent increase in the onshore literature compared to stagnant numbers of articles investigating primarily offshore produced water (Figure 3-18 A). Consistent with increasing interest in alternative applications for onshore produced water produced water, there is a rising number of publications related to agricultural uses, treatment and remediation, biomarker discovery to track exposures, and human health impacts in recent years.

Potential risks from produced water with special emphasis on hydraulic fracturing

Risk perception of produced water effluents is linked to compositional concerns and biological evidence derived from environmental and human health related toxicological studies. Produced waters are complex mixtures comprising a wide array of naturally occurring and man-made chemicals, predominantly salts, hydrocarbons (e.g., mono and polyaromatic compounds) and low molecular weight acids, but also potentially harmful contaminants including metals and radioactive materials (Figure 3-18 B–C). Recent evidence indicates that conditions during unconventional oil and gas operations can be favorable for catalysis or halogenation of aromatic constituents. Environmental concerns thus stem from both salinity and xenobiotic exposures to harmful contaminants. Laboratory and field studies provide further evidence for harmful properties of produced water, reporting adverse effects on various marine, aquatic and terrestrial organisms, including acute and chronic toxicity, mutagenic, developmental and reproductive effects, and potential for endocrine disruption. Comparably few studies have specifically addressed human health concerns of produced water. In most cases, excess lifetime cancer risk was estimated to be negligible, but non-cancer health risks appear to warrant further evaluation due to limited exposure data particularly for metals.

Most of the peer-reviewed literature focuses on assessing effects of untreated produced water and/or individual, often concentrated, chemical fractions of produced water. As treatment and remediation procedures, for example by desalination, electro-oxidation, and photo (electro) catalysis, continue to improve the quality of produced water streams, these treatments will likely reduce associated toxicities, e.g., mutagenicity, by removing associated constituents of concern from the produced water.

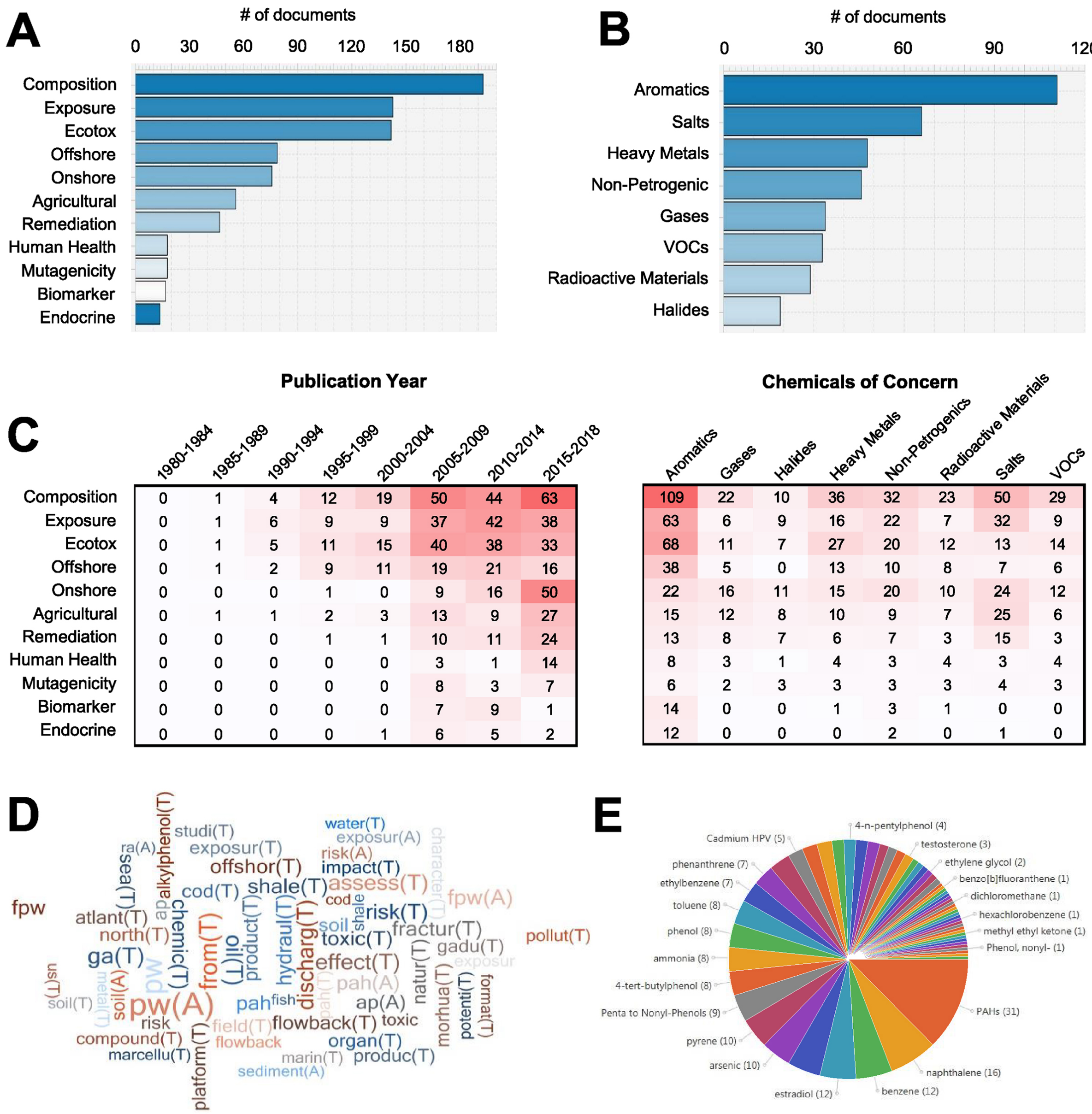


Figure 3-18: Software-Assisted Literature Evaluation and Trend Analysis

Search hits were analyzed in Sciome Workbench for Interactive Computer-Facilitated Text-mining (SWIFT). (A) Total number of search hits associated with major search categories; (B) Number of search results for major classes of chemical constituents of produced water; (C) Heatmap representation of temporal and chemical constituent-based publication trends; (D) Search term frequency-based fingerprint of all relevant search results; (E) Search term-recognition based publication hits related to endocrine-disrupting chemicals. [Abbreviations: T=title, A=abstract, EDC=endocrine disrupting chemical, VOC=volatile organic compound]

Constituents related to produced water

Produced waters are often high in total dissolved solids (TDS) and halides (e.g., chloride, bromide, fluoride), and may contain metals (antimony, arsenic, barium, beryllium, boron, cadmium, chromium, cobalt, copper, lead, lithium, mercury, molybdenum, nickel, selenium, silver, strontium, thallium, vanadium, zinc, uranium and thorium), and NORMs such as ^{226}Ra and ^{228}Ra (Figure 1B) (Birkle et al. 2005, Mofarrah et al. 2011, Lampe et al. 2015, Bzowski et al. 2015, Chittick et al. 2017, Luek et al. 2017). The concentration of individual constituents can be highly variable and depends on the geologic characteristics of the formation (Bou-Rabee et al. 2009, Bzowski et al. 2015). Produced water that contains flowback water from hydraulic fracturing operations may contain a variety of chemicals that comprise fracturing fluids (Table 3-3).

Produced waters may also contain a wide range of concentrations of volatile and semi organic compounds (VOCs and SVOCs) that originate from contact with the crude oil/ gas or are introduced by drilling fluids. Among the most common VOCs are BTEX (benzene, ethyl-benzene, toluene, and all xylenes), mixed alkanes, and naphthalene (Luek et al. 2017). Similarly, a wide variety of aromatic compounds including alkylated benzenes, alkylated naphthalene's, PAHs, phenanthrenes, phenols, and pyrene have been reported in a number of studies characterizing produced water (Chittick et al. 2015, Luek et al. 2017). Several gases such as methane, hydrogen sulfide, and carbon oxides can be found dissolved in produced water and can be released into ambient air. Fracking fluids include a mixture of a wide variety of non-petrogenic substances, including acids, biocides, corrosion inhibitors, pH control agents, and gellants (Table 3-3).

Last, a combination of physical, chemical and biologically mediated reactions may transform fracking fluid or geogenic substances. A number of small organic acids are produced through microbial transformation under the anaerobic conditions; acetates are a byproduct of the degradation of organic additives; and halogenated organic compounds can be formed when hydrocarbons are in contact with halogenated salts or biocides suggesting that halide salts or free halogens are created during oxidative treatments can cause the observed halogenation (Luek, 2017). Other disinfection by-products can be formed during the treatment of produced waters, especially those with high contents of chlorides, bromides, or other halides.

Table 3-3: Summary of the Types of Chemicals Commonly Used in Hydraulic Fracturing*

Type	Function	Selected Examples
Acids	Improve injection or penetration; dissolve minerals	Hydrochloric acid
Biocides	Prevent bacterial growth, which can erode pipes	Glutaraldehyde; Quaternary ammonium compounds; Tetrakis hydroxymethyl phosphonium sulfate
Breakers	Break down of gellants; added to enhance flowback	Ammonium persulfate; Sodium, calcium chloride; Magnesium oxide; Magnesium peroxide
Clay stabilizers	Prevent clay plugs of fractures	Choline chloride; Sodium chloride; Tetramethyl ammonium chloride
Corrosion inhibitors	Reduce rusting	Isopropanol; Methanol; Formic acid; Acetalde-hyde
Crosslinker	Maintain fluid viscosity; may include carrier fluids	Potassium metaborate; Triethyanolamine zirconate; Petroleum distillate; Boric acid; Zirconium; Sodium tetraborate
Friction reducers	Enhance efficiency of fluid movement	Polyacrylamide; Methanol; Ethylene glycol; Petroleum distillate
Gellants	Increase viscosity and suspend sand during proppant transport	Guar gum; Polysaccharide blend; Ethylene glycol; Hydrotreated light petroleum distillate
Iron control	Prevent precipitation of metal oxides	Citric acid; Acetic acid; Thioglycolic acid; Sodium erythorbate
Non-emulsifier	Prevent formation of emulsions, and as a product stabilizer	Lauryl sulfate; Isopropanol; Ethylene glycol
pH control	Maximize effectiveness of other additives	Sodium hydroxide; Potassium hydroxide; Acetic acid; Sodium carbonate
Proppants	Hold fissures open for gas & oil escape	Silica (quartz; sand)
Scale control	Prevent mineral buildup and clogs	Copolymer of acrylamide and sodium acrylate; Sodium polycarboxylate; Phosphonic acid salt
Surfactants	Decrease surface tension and improve fluid passage	Lauryl sulfate; Ethanol; Naphthalene; Methanol; Isopropyl alcohol; 2-butoxyethanol

* Adapted from FracFocus, https://fracfocus.org/chemical-use/what-chemicals-are-used.

Assessments identifying endocrine disrupting chemicals

Endocrine disruption is a term describing complex chemical interactions with endocrine systems in living organisms, which can lead to adverse outcomes including developmental effects and carcinogenicity. Certain PAHs, alkylated PAHs, alkylphenols (AP), naphthol's, and naphthenic acids (NA) have been linked to endocrine-disrupting effects in marine biota, and the presence of these and other chemicals with potential endocrine disrupting potential (Figure 3-18 E) in produced water has raised awareness, especially with respect to fresh and salt water environments. APs have emerged as chemicals of primary concern with currently 52 unique structures being confirmed in produced water streams from nine different locations in the North Sea and Norwegian Sea (Boitsov et al. 2007).

In addition to the presence of chemicals of concern, evidence exists from laboratory studies supporting endocrine disrupting potential of untreated produced water or its individual constituents in fish and in vitro models. Estrogen (ER) and androgen receptor (AR) activities are indicative of potential for progression of certain breast and prostate cancers in humans and are among the best studied endocrine phenotypes. At the molecular level, produced water exposure has been correlated with increases in plasma concentrations of the estrogenic activity marker vitallogenin (Geraudie et al. 2014; Sundt et al. 2011). Corroborating evidence for these observations stems from in vitro estrogen receptor assays demonstrating the presence of ER active constituents and androgen receptor AR activity in vitro. However, consistent with geological variation, results varied significantly across multiple produced water samples, including samples without associated endocrine activity. Thomas et al. (2009) evaluated individual fractions of produced water samples, concluding that short-chain APs and naphthenic acid contribute approximately 35% and 65% of the ER agonist activity. Knag et al. (2013) observed AR activities in freshwater fish treated with commercial mixtures of NAs. Altogether, these studies demonstrate that petrogenic constituents are major contributors to produced water-associated ER/AR activities. Knag et al. (2013) also reported estradiol and progesterone induction and inhibition of testosterone production in human H295R cells exposed to APs, NAs, and the polar fraction of produced water. At the organism level, exposure of zebrafish embryos to high concentrations of isolated organic fractions of produced water resulted in developmental effects included spinal malformations, hatch delay, and pericardial edema (He et al. 2018).

Evidence-generating studies

As noted in the introduction to part 1 of this section, the scope of this review was broad enough to gather information from a wide variety of sources deemed informative in some way to assessing produced water, its chemical characterization, and potential impacts from its release or reuse. Some papers include offshore produced water analysis, while others focus on analyzing the constituents used in operations and potentially present in produced water, untreated produced water, and even spill impacts. In all cases, where data exists to better understand produced water there presents an opportunity to gather information that can inform more targeted assessments such as prioritizing chemicals for analytical method development or focusing research objectives for a particular reuse scenario.

Exposure considerations

Occupational exposures to the salts and radioactive materials can occur during handling and deposition of the precipitate or filtration cakes, handling of the solids, or resuspension of the material during transport and/or after deposited. The present literature review did not identify studies specifically addressing these concerns.

When considering surface application for dust abatement, irrigation of crops, or livestock water supply, there is potential for the accumulation of metals, salts, and NORM in the soil matrix. Occupational and non-occupational exposures can occur due to contact with contaminated soil, indirect soil ingestion, or ingestion of crops irrigated with these waters. Several studies on produced water spills to soil report that NORM and metals tend to be sorbed onto nearby soil and not transported far from the spill location (Birkle et al. 2005), but do not address the potential direct or indirect exposure to contaminated soils through ingestion, inhalation, or contact or mechanical dispersion from tires or dust. At least one study has evaluated the potential risks of contact with contaminated soils, reporting potential non-cancer endpoints

(Mofarrah et al. 2011). Human exposure can result from consumption of contaminated food that has been in contact with produced water contaminants (Mofarrah et al. 2011, Werner et al. 2015); but the significance of these pathways has not been reported in the literature.

Most of the air quality concerns addressed in the literature are concerned with venting, fugitive gas emissions and diesel emissions during operations. No studies were identified that evaluated potential air exposures during beneficial reuse of produced water. Similar to emissions during operations, storage of produced water in open air pits, aeration, or dispersion of produced water may lead to the emission of volatile organic compounds such as BTEX, CO, H2S, NOx and even particulate matter (including crystalline silica and heavy or rare metals) (Lampe et al. 2015, Chitick et al. 2017). These emissions will mainly lead to occupational exposures but may also impact air quality in nearby communities.

Human health

The human health literature consists largely of theoretical attempts to conduct health hazard/risk assessments for spill scenarios, with most studies focusing on quantifying cancer risk, although some examine both cancer and non-cancer endpoints. Overall, the literature is characterized by variation in the target population (occupational, residential), exposure scenarios (swimming in a contaminated pond, use of contaminated reservoir for residential drinking water supply), exposure route (inhalation, dermal, oral) and assumptions (length of exposure, time to event, dilution rate) and model choice (deterministic, fuzzy rule-based, Monte Carlo). Some exposure scenarios consider operations that may no longer be practiced in certain regions (e.g., open-air storage of flow back water) and therefore may not be relevant to an assessment of a particular application or reuse scenario. Given the dates of publication for most of the papers, this appears to be a growing area of study (Figure 3-18 B).

Results of the identified body of literature are challenging to summarize given the differences across studies and dearth of total studies. The health effects literature reveals mixed results and should be interpreted with caution. Although some studies report excess lifetime cancer risks (among the general population) between 10^{-10} to 10^{-6} under various dermal, inhalation and ingestion scenarios due to radionuclide exposure (Abualfaraj et al. 2018; Rish et al. 2018; Torres et al. 2018), other studies that evaluated cancer risk related to radioactive materials exposure (Shakhawat et al. 2006) or exposure to polycyclic aromatic hydrocarbons (Chowdhury et al. 2009) observed no significant increases in cancer risk.

Non-cancer hazard index has also been examined in risk assessments of produced water, with similarly mixed results. Barium and thallium were associated with increased risk for non-cancer outcomes (Abualfaraj et al. 2018), whereas in an assessment of non-cancer outcomes due to metals exposure, risk was reported to be well within acceptable limits (Mofarrah et al. 2011).

Worker health has also been considered in the produced water literature. In a study that examined health risks of inhalation exposure to 12 volatile organic compounds (VOC) present in flow back water, Bloomdahl et al. (2014) did not observe an increased risk of adverse health effects due to any of the VOC measured, whether modeled as hazard quotients, hazard indices or excess lifetime cancer risk. In an assessment of cancer risk due to dermal exposure among workers, Durant et al. (2016) observed few substances (benzo(a)pyrene, heptachlor, and barium) related to excess cancer risk i.e. exceeding 10^{-6}.

Ecological receptors

- **Freshwater life**. Fracturing fluids and onshore produced water (which may contain flowback containing residual substances used in fracturing fluids, maintenance and production, as well as transformation products) have been characterized with regard to mostly freshwater aquatic wildlife, typically stream-dwelling fish and invertebrates. Effect levels are highly dependent on the produced water type and the associated hydrocarbon formation, i.e., oil, gas, or coalbed methane (CBM), also referred to as coalbed natural gas, coal seam gas.

  Among the contaminants exerting the greatest ecotoxicity concern in fresh waters, dissolved salts (TDS comprised primarily of major ions Na+, Ca++, Mg++, K+, Cl-, SO42-, HCO3-) are the most abundant and due to their high solubility in water, they can exert a strong influence on species distribution. In dried salts or reject brines from treating produced water from conventional and shale operations, metals and NORM are concentrated, elevating the potential hazards of the salts. TDS consisting mostly of NaCl can be over 250,000 mg/l in some shale gas produced waters, e.g., from the Marcellus and Bakken formations. Additional minerals arising from produced water whose effects on freshwater aquatic life have been measured include barium (Golding et al. 2018), iron and manganese (Duarte et al. 2018).

Freshwater organisms are sensitive to TDS over a range of concentrations beginning at less than 1,000 mg/l, based on conductivity (a generic reflection of saltiness; Cormier et al. 2013). CBM produced water (CBMPW) comes from shallow formations and tends to be brackish rather than briny, and less laden with associated metals and petroleum hydrocarbons than produced water from unconventional production and may be suited for discharge to streams after minimal treatment (USGS 2000). Farag and Harper (2014) evaluated toxicity of sodium bicarbonate in CBM simulated waters to develop a species sensitivity distribution of common laboratory and receiving stream (Powder River, Wyoming) species, concluding inhibitory concentrations between 500-1000 mg/l may be exceeded in undiluted produced water.

Organic contaminants from the formation and also from fracturing fluid are present in some produced water and exert toxicity to freshwater organisms (Butovskyi et al. 2017) including PAHs (He et al. 2017), alkylpenols (Holth et al. 2008) and quaternary amine compounds. Organism responses evaluated range from invertebrate survival and growth (Blewett et al. 2017) to swimming proficiency, cardiotoxicity, respirometry, transcriptomics and biomarkers in zebrafish (*Danio rerio*) (Folkerts et al. 2017; Holth et al. 2008), providing a range of response endpoints as dilutions of produced water constituents.

- **Marine life.** Effects of produced waters on marine organisms have been well-studied, concomitant with a lengthy history of offshore produced water discharges (Figure 1B). Offshore produced water discharges rely on dilution by seawater and movement by ocean currents to limit exposure of marine organisms to produced water contaminants. Ecotoxicity screening of many produced waters from platforms, discharge sampling points, and the edges of mixing zones demonstrates that while undiluted marine produced water is typically toxic, it is diluted to below organism-effect levels within a short distance of the discharge point. Nevertheless, the body of literature regarding marine species details methods and findings that may be transferable to land-based discharge options.

In the past two to three decades increasing interest has been focused on biomarkers of exposure of cod (Gadus morhua) in the North Sea, where fish migratory grounds intersect a high number of platforms. These include effects on acetylcholinesterase (ACHE, neurotransmitter), oxidative stress proteins, and DNA damage, among a broad number of molecular tools (Hasselberg et al. 2004, Sturve et al. 2006, Holth et al. 2010, 2011a, 2012). There is some indication of broad-reaching presence of produced-water induced biomarkers in the North Sea (Balk et al. 2011). As noted by Holth (2010), the biomarkers need to be tied to physiological effects in order to be incorporated into risk assessments. Additionally, it has been observed biomarker up-regulation early in exposure often gives way to compensatory pressures as organisms acclimate to new conditions, which complicate use of biomarkers in decision-making (Abrahamson et al. 2008).

Studies using marine mussels are generally focused on bioaccumulation of produced water contaminants, primarily PAH parent and alkyl-substituted congeners (Brooks et al. 2011). PAH fingerprinting indicates in many settings the mussels are exposed to both petrogenic and pyrogenic sources, though the source of pyrogenic emissions is uncertain. Solid-phase extraction of PAH from seawater provides similar to slightly-higher results, indicating biomimetic extraction using passive sampling could be used instead of mussel (or oyster) tissue monitoring (Durell et al. 2006; Harman et al. 2011).

- **Livestock.** A limited number of studies considered livestock watering as a potential beneficial use of produced water (Horner et al. 2011) or coalbed natural gas produced waters (Jackson and Reddy, 2007a; Zhang and Qin, 2018), with only Horner et al. (2011) specifically conducting a series of conceptual risk evaluations to assess the aggregate risk of the various produced water chemicals in several livestock species, including drinking water and dietary intake exposure pathways.
- **Agriculture and soil biota.** Irrigation of crops and soil, or spillage to soil, risks impairing soil function by decreasing water permeation. Direct effects of irrigation water on sensitive crops may also occur. Non-food crops are often preferred for irrigation reuse in order to avoid direct ingestion pathways. Sunflowers (DaCosta et al. 2015, Sousa et al. 2017), castor beans (deMeneses et al. 2017), switchgrass and wormwood (Artemisia) (Burkhardt et al. 2015a, 2015b), and switchgrass and rapeseed (Pica et al. 2017) were exposed to untreated and treated produced waters with a wide variety of results related to product quality and yield, though most indicate at least short-term use with either processed produced water or untreated CBM produced water is acceptable in terms of plant performance, and soil: water ionic interactions. Reverse-osmosis (RO) treatment is not always beneficial to crops. Ferreira et al. (2015a) characterized soil mesofauna and found the produced water that had undergone RO had significant effects on species composition, richness and abundance. Sousa et al. 2016 examined the sunflowers grown in that study and found differences in mineral sequestration with filtered and treated (RO), favoring RO.

Effects of remediation and treatment

Among the potential reuse options for produced water, often after treatment, are surface water discharge, livestock watering, irrigation (crop and/or non-food), aquaculture, industrial applications, and dust abatement in roads (Long et al. 2015, Chittick, 2017). In a general sense, water quality for irrigation should be sufficient to 1) protect human health when consuming food produced from crops irrigated with reclaimed wastewater; 2) minimize soil contamination through metal and salt loading; and 3) prevent crop growth inhibition or quality degradation. Bioaccumulation should also be considered. Livestock watering guideline values should be sufficiently stringent to minimize health risks to livestock to ensure successful production. These requirements determine the degree of produced water treatment prior to beneficial reuse.

Produced water treatment in publicly owned treatment works (POTWs) for discharge into receiving streams may impair biological treatment processes, accumulate contaminants in sewage sludge, or facilitate the formation of harmful disinfection byproducts (Chittick, 2017). This is primarily due to the treatment processes at POTWs not being designed to treat this type of water. As a result, unconventional produced waters are no longer permitted to be discharged directly to POTWS in the US, though conventional discharges and indirect discharges from centralized waste treatment facilities are allowed. produced water evaporation in large, open pits allows for oil and grease to be skimmed off the surface while the remaining water is moved to one or more other pits for evaporation or further management. Potential exposure to air emissions associated with this practice should be considered, as air measurements have reported VOCs (particularly benzene) levels above EPA screening levels (Chittick, 2017). A similar process is the solar evaporation or distillation and crystallization of the produced water. In addition to the potential exposure to air emission of VOCs with this process, of consideration is the potentially large volumes of waste that has concentrated heavy and rare earth metals in these residues that must be disposed or otherwise managed (e.g., potential for recycling/reuse or further extractions for sales in certain circumstances).

Constructed wetland treatment systems used for targeted treatment of produced waters demonstrably enhance characteristics of produced water. Alley et al. 2014 found that various hydrocarbon and metal markers decreased in excess of 99% and 98%, providing the required efficiency to alleviate ecotoxicity to Ceriodaphnia and fathead minnows. Toxicity of oil sands produced water also decreased, along with metals concentrations, in a hybrid constructed wetland capable of both oxidizing and reducing conditions (Hendrikse et al. 2018).

Other options for produced water treatment include the membrane filtration and reverse osmosis, among others (see the Technology section of this Module). These processes tend to be energy intensive and may not feasible for produced water with high TDS or contamination with gelling agents. Biodegradation of produced water constituents of concern using microorganisms or crops is being tested with different degrees of success, with the salinity of the produced water being a major factor in success of the tests. By contrast, chemical degradation of contaminants using electro-oxidation or photo(electro)catalysis has been reported to provide an effective means to greatly reduce mutagenic activity associated with concentrated organic fractions of produced water samples, thereby indicating the possibility to alleviate this hazard (Li et al. 2006; Li et al. 2007).

Knowledge gap analysis

The following sections highlight uncertainties and knowledge gaps represented by studies that were reviewed as well as highlight research needs that may be associated with those identified gaps.

Analysis of chemical constituents of toxicological concern

Advances in analytical capabilities have improved routine characterizations of produced water composition. However, inherent complexity and variability of produced water due to geologic origin, additives, and decomposition byproducts affects the efficiency of treatment processes, estimates of exposures to constituents of concern, and hazardous properties. Chen et al. (2017) concluded that both uncertainty in existing data as well as a lack of exposure data have prevented risk assessments to move beyond modeling based on spill scenarios. Since beneficial use of produced water outside oil and gas operations is relatively limited compared to internal recycling and deep well injection, very few studies have evaluated the potential for chronic exposures due to direct or indirect exposure pathways that may be involved with reuse.

Endocrine disruption

Current knowledge on endocrine disrupting potential of constituents of produced water is mostly limited to few selected endpoints, particularly estrogen (ER) and androgen receptor (AR) activities, in fish or *in vitro*.

Field studies

Current risk assessments are predominantly based on spill scenarios of untreated produced water, thereby limiting their utility in appropriate evaluation on environmental and human health risks of produced water in specific reuse scenarios.

Evidence-generating studies involving receptor exposures

- **Human health.** Heterogeneity across studies/assessments greatly limit comparability between different study results and our understanding of potential adverse health effects due to produced water exposure. The primary limitation of the existing literature stems from the uncertainty related to exposure and hypothesized pathways that could theoretically pose an increased risk for adverse outcomes. As the literature currently stands, each risk assessment represents a unique case study of a particular exposure scenario, the relevance of which is not known, complicating the interpretation of the results.
- **Ecological receptors.** Terrestrial receptors may also be impacted by exposure to produced water contaminants – in particular, those species occupying the riparian zone of streams where higher exposures of produced water discharges or runoff could occur – birds, reptiles and amphibians, small mammals, and invertebrates particularly insects, as well as plant life. Within fresh water bodies, there appears to be a dearth of information regarding species sensitivity ranges, as many tests have been conducted using standardized species (e.g., daphniids, fathead minnows, or zebrafish) with only limited studies involving freshwater mollusks including rare/ threatened/ endangered freshwater mussels; aquatic insects and other arthropods; aquatic plants; and native fish inhabiting the water column or benthos.

APPENDIX 1-A: Obtaining an NPDES Permit for Produced Water Discharges in Arkansas

This case example was provided by Southwestern Energy.

Background

The Fayetteville Shale is a dry natural gas play that was discovered in 2004. Figure 1-A-1 shows a map of the formation. Southwestern Energy holds approximately 925,000 net acres in the play. Between 2004 and 2013, Southwestern Energy completed more than 3,750 wells. It should be noted that typically only 10 to 15% of the water utilized in completing Fayetteville wells is ultimately recovered as produced water.

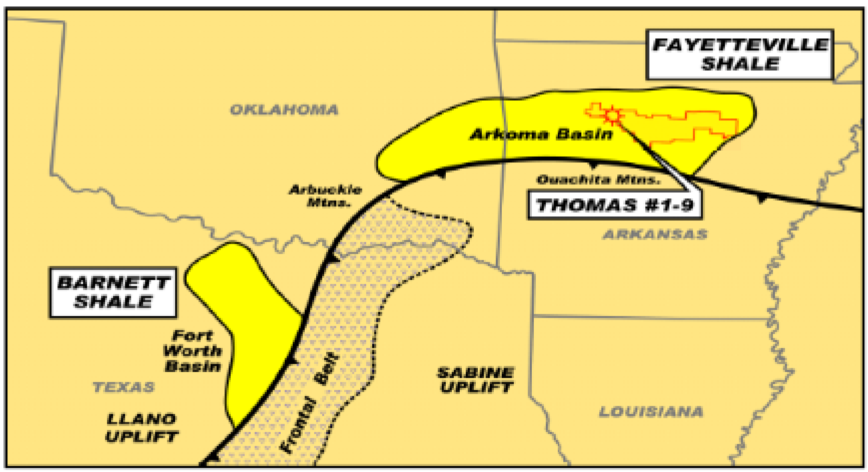


Figure 1-A-1 – Map of Fayetteville Shale   Source: Southwestern Energy

Originally, saltwater disposal wells (SWD) were primarily used for disposal of the recovered water. However, in August 2011, the Arkansas Oil and Gas Commission (AOGC) issued an Order to prohibit disposal injection wells in certain portions of Cleburne, Faulkner, Van Buren, and Conway counties because of local earthquakes related to a previously unknown or unmapped fault system (Reference AOGC Order No. 180A-2-2011-07). Figure 1-A-2 shows the Permanent Disposal Well Moratorium Area defined by the AOGC that covers portions of the Fayetteville Shale. This map may also be found on AOGC's website at: http://www.aogc.state.ar.us/sales/Disposal_Wells_Area.pdf.

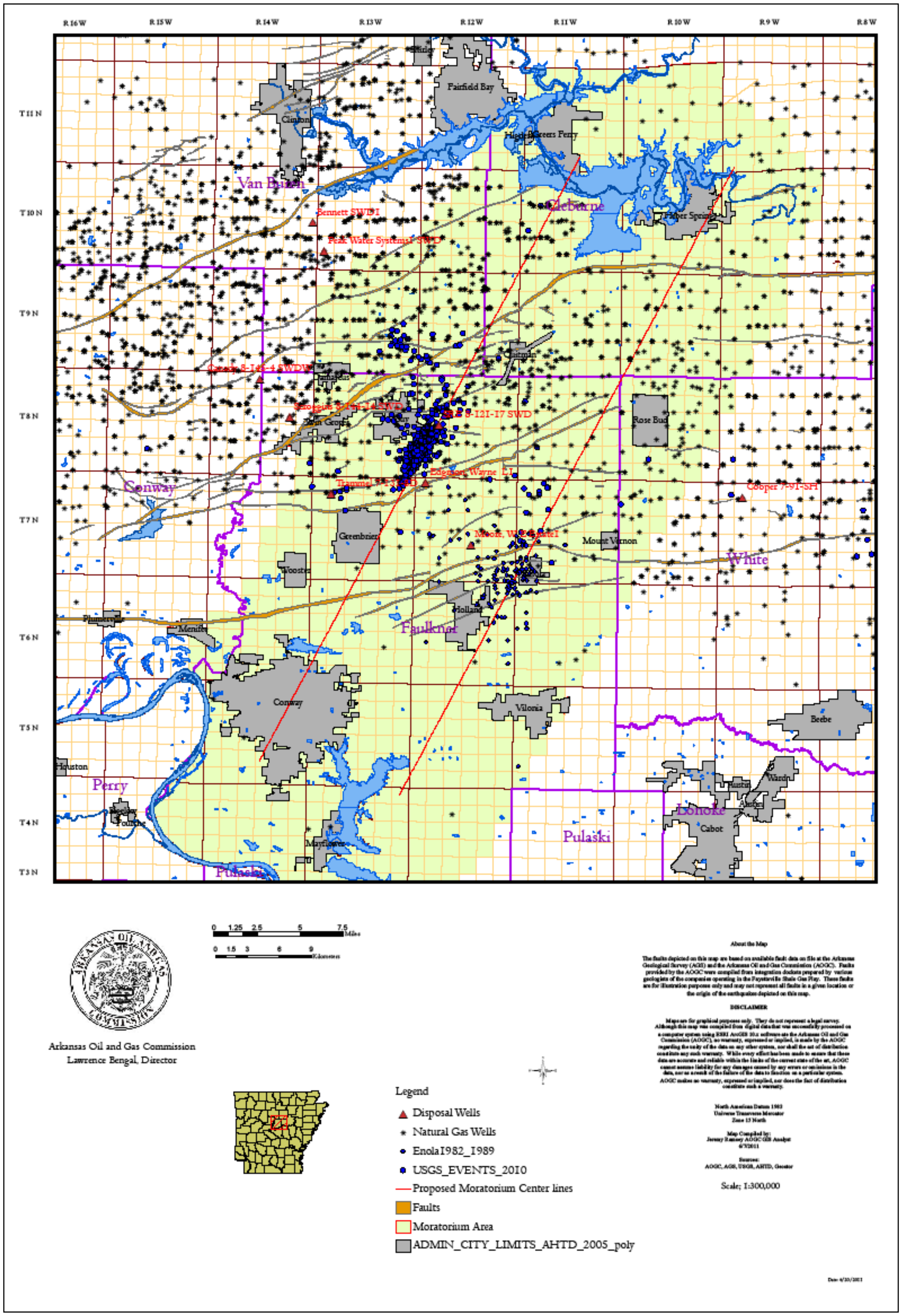


Figure 1-A-2 – Permanent Disposal Well Moratorium Area Source: Arkansas Oil and Gas Commission

The net operational impact of the disposal moratorium area was to limit access to local SWD wells, which resulted in the need to transport water via trucks longer distances. This increased Southwestern Energy's drive to look for alternative means of managing our water recovered from wells.

Permitting Efforts

Southwestern Energy's initial focus was to continue increasing its recycling efforts of the recovered water, utilizing the water locally in our operations. At the same time, Southwestern began exploring other alternatives that would be a reliable, economical option to reuse or disposal some distance away. One potential solution was to treat and discharge the water to the surface via NPDES permit. Unfortunately, the Effluent Limit Guidelines (ELGs) listed in 40 CFR 435 provide for the discharge of oil and gas effluent west of the 98th Meridian, but not to the east, where Arkansas is located. This led Southwestern Energy to pursue an alternative to allow for surface discharge of treated water under a different regulation, 40 CFR 357. Centralized Waste Treatment (CWT) facilities are defined in 40 CFR 437.2(c) as: "…any facility that treats (for disposal, recycling or recovery of material) any hazardous or non-hazardous industrial wastes, hazardous or non-hazardous industrial wastewater, and /or used material received from off-site."

Southwestern Energy and its consultant approached the Arkansas Department of Environmental Quality (ADEQ) about applying for an NPDES permit for a CWT facility. A third-party company had already applied for a CWT permit in the state using mechanical vapor recompression (MVR) as the primary method for desalination of the water before discharge. Once both the ADEQ and Southwestern Energy agreed that the CWT was an appropriate approach for treating and discharging water, Southwestern prepared permit applications for two locations within the Fayetteville Shale play that would utilize a similar technology to the one in the initial third-party company permit. The two locations were selected primarily due to their locations and proximity to Southwestern Energy's major areas of water production with the intent to minimize transportation costs of the water to the facility. Also taken into consideration was road access to the site as trucks are the primary means of transporting produced water from the well pads.

Once the sites were selected, applications were prepared for each site. These applications utilized the standard NPDES application forms utilized by the ADEQ which include both EPA Form 3510-2D (New Sources and New Dischargers: Application and for Permit to Discharge Process Wastewater) and ADEQ NPDES Application Form 1. Supplemental information to the forms was provided as well to support the application including:

- Information on the selected treatment process,
- Water quality data from the proposed treatment system when utilized to treat water for another operator not in Arkansas,
- Topographical maps, and
- Other complementary material.

ADEQ developed the NPDES permits and the corresponding discharge limits based on the water body into which each permit site proposed to discharge, the stream flows and existing water quality, technological based limits that were available at the time, as well as data submitted by Southwestern Energy on the expected quality of the water that was to be treated.

Once the permits were drafted and agreed to by both ADEQ and Southwestern Energy, the permits were published for public comment. ADEQ addressed the public comments per the state rules and regulations and the permits were issued to Southwestern Energy in 2012 and 2013 (AR0052051 and AR0052175). The extensive list of effluent limits included in permit AR0052051 is shown in Table 1-A-1.

Southwestern Energy elected to build and install only one treatment system initially at the eastern facility (AR0052051), in part due to the facility being located farthest from Southwestern Energy's own SWDs and commercially available SWDs. A permit for a third site (AR0052086) was obtained in 2013 but never constructed for economic reasons.

PART I
PERMIT REQUIREMENTS
SECTION A. EFFLUENT LIMITATIONS AND MONITORING REQUIREMENTS; OUTFALL 001 – treated fluids from the exploration, production, and development of oil and/or gas operations.

During the period beginning on the effective date and lasting until the date of expiration, the permittee is authorized to discharge from Outfall 001.

Such discharges shall be limited and monitored by the permittee as specified below:

Effluent Characteristics	Discharge Limitations				Monitoring Requirements	
	Mass (lbs/day, unless otherwise specified)		Concentration (mg/l, unless otherwise specified)		Frequency	Sample Type
	Monthly Avg.	Daily Max.	Monthly Avg.	Daily Max.		
Flow	N/A	N/A	Report, MGD	Report, MGD	daily	totalizing meter
Carbonaceous Biochemical Oxygen Demand ($CBOD_5$)	14.0	21.0	10.0	15.0	once/month	grab
Total Suspended Solids (TSS)	21.0	31.5	15.0	22.5	once/month	grab
Ammonia Nitrogen (NH3-N)						
(April)	7.8	7.8	5.6	5.6	daily	grab
May-Oct)	7.0	10.5	5.0	7.5	daily	grab
(Nov-March)	14.0	21.0	10.0	15.0	daily	grab
Dissolved Oxygen (DO)	N/A	N/A	2.0 (Inst.Min.)		daily	grab
Chlorides	131.7	197.6	94	141.0	daily	composite
Sulfates	28.0	42.0	20.0	30.0	daily	composite
Total Dissolved Solids (TDS)	496.0	744.0	354.0	531.0	daily	composite
Oil and Grease (O&G)	14.0	21.0	10.0	15.0	daily	grab
Arsenic, Total Recoverable (Ar)	1.9	4.1	1.33	2.95	once/month	composite
Cadmium, Total Recoverable (Cd)						
(May-Oct)	0.0026	0.0052	1.8 µg/l	3.7 µg/l	once/month	composite

Effluent Characteristics	**Discharge Limitations**				**Monitoring Requirements**	
	Mass (lbs/day, unless otherwise specified)		**Concentration (mg/l, unless otherwise specified)**		**Frequency**	**Sample Type**
	Monthly Avg.	**Daily Max.**	**Monthly Avg.**	**Daily Max.**		
(Nov-April)	0.0075	0.015	5.4 µg/l	10.8 µg/l	once/month	composite
Chromium III, Total Recoverable (Cr3)						
(May-Oct)	0.41	0.83	295.4 µg/l	592.8 µg/l	once/month	composite
(Nov-April)	1.2	2.4	860.1 µg/l	1725.7 µg/l	once/month	composite
Chromium (VI) (Cr6)						
(May-Oct)	0.017	0.033	11.8 µg/l	23.7 µg/l	once/month	composite
(Nov-April)	0.038	0.076	26.9 µg/l	54.1 µg/l	once/month	composite
Chromium, Total Recoverable (Cr)	0.45	1.05	323 µg/l	746 µg/l	once/month	composite
Cobalt, Total Recoverable (Cu)	26.3	79.0	18.8 µg/l	56.4 µg/l	once/month	composite
Copper, Total Recoverable (Hg)						
(May-Oct)	0.013	0.026	9.2 µg/l	18.5 µg/l	once/month	composite
(Nov-April)	0.026	0.053	18.8 µg/l	37.8 µg/l	once/month	composite
Lead, Total Recoverable (Pb)						
(May-Oct)	0.0038	0.0076	2.7 µg/l	5.4 µg/l	once/month	composite
(Nov-April)	0.011	0.022	7.9 µg/l	15.8 µg/l	once/month	composite
Mercury, Total Recoverable (Hg)						
(May-Oct)	0.000019	0.000038	0.013 µg/l	0.027 µg/l	once/month	composite
(Nov-April)	0.000055	0.000011	0.039 µg/l	0.078 µg/l	once/month	composite
Nickel, Total Recoverable (Ni)						
(May-Oct)	0.14	0.27	97.0 µg/l	194.6 µg/l	once/month	composite
(Nov-April)	0.40	0.79	282.3 µg/l	566.4 µg/l	once/month	composite

Table 1-A-1 Effluent Limitations and Monitoring Requirements. Source: After USEPA

Permit Number: AR0052051
AFIN: 73-01167
Page 2 of Part IA

Effluent Characteristics	**Discharge Limitations**				**Monitoring Requirements**	
	Mass (lbs/day, unless Otherwise specified)		**Concentration (mg/l, unless Otherwise specified)**		**Frequency**	**Sample Type**
	Monthly Avg.	**Daily Max.**	**Monthly Avg.**	**Daily Max.**		
Silver, Total Recoverable (Ag)						
(May-Oct.)	0.0013	0.0026	0.93 µg/l	1.87 µg/l	once/month	composite
(Nov-April)	0.0025	0.0051	1.8 µg/l	3.6 µg/l	once/month	composite
Tin, Total Recoverable (Sn)	0.23	0.47	165.0 µg/l	335.0 µg/l	once/month	composite
Zinc, Total Recoverable (Zn)						
(May-Oct)	0.12	0.24	85.5 µg/l	171.6 µg/l	once/month	composite
(Nov-April)	0.23	0.47	166.0 µg/l	333.2 µg/l	once/month	composite
Cyanide, Total Recoverable (CN)					once/month	composite
(May-Oct)	0.008	1.016	5.8 µg/l	11.6 µg/l	once/month	composite
(Nov-April)	0.024	0.047	16.9 µg/l	33.9 µg/l	once/month	composite

Effluent Characteristics	Discharge Limitations				Monitoring Requirements	
	Mass (lbs/day, unless Otherwise specified)		Concentration (mg/l, unless Otherwise specified)		Frequency	Sample Type
	Monthly Avg.	Daily Max.	Monthly Avg.	Daily Max.		
Bis (2-ethylhexyl) phthalate	0.14	0.30	0.101	0.215	once/month	composite
Butylbenzyl phthalate	0.12	0.26	0.0887	0.188	once/month	composite
Carbazole	0.39	0.84	0.276	0.598	once/month	composite
n-Decane	0.61	1.33	0.437	0.948	once/month	composite
Fluoranthene	0.038	0.075	0.0268	0.0537	once/month	composite
n-Octadecane	0.42	0.83	0.302	0.589	once/month	composite
Radium-226 (dissolved)	N/A	N/A	Report pCi/l[1]	Report pCi/l[1]	once/quarter	grab
Strontium-90 9dissolved)	N/A	N/A	Report pCi/l[1]	Report pCi/l[1]	once/quarter	grab
Beta radiation (gross)	N/A	N/A	Report pCi/l[1]	Report pCi/l[1]	once/quarter	grab
pH	N/A	N/A	Minimum 6.0 s.u.	Maximum 9.0 s.u.	daily	grab
Chronic WET Testing[2]	N/A	N/A	Report			
Pimephales promelas (Chronic) Pass/Fail Lethality (7-day NOEC) TLP6C Pass/Fail Growth (7-day NOEC) TGP6C Survival (7-day NOEC) TOP6C Coefficient of Variation (Growth) TQP6C Growth (7-day NOEC) TPP6C			7-Day Average Report (Pass=0/Fail=1) Report (Pass=0/Fail=1) Report % Report % Report %		 bi-monthly bi-monthly bi-monthly bi-monthly bi-monthly	24-hr composite
Ceriodaphnia dubia (Chronic) Pass/Fail Lethality (7-day NEOC) TLP3B Pass/Fail Reproduction (7-day NOEC) TGP3B Survival (7-day NOEC) TOP3B Coefficient of Variation (reproduction) TQP3B Reproduction (7-day NOEC) TPP3B			7-Day Average Report (Pass=0/Fail=1) Report (Pass=0/Fail=1) Report % Report % Report %		 bi-monthly bi-monthly bi-monthly bi-monthly bi-monthly	24-hr composite

[1] picoCuries/liter

[2] See Condition No. 5 of Part II (WET Testing Requirement). There shall be no discharge of distinctly visible solids, scum, or foam of a persistent nature, nor shall there be any formation of slime, bottom deposits, or sludge banks. There shall be no visible sheen as defined in Part IV of this permit Samples and measurements taken as required herein shall be representative of the volume and nature of the monitored discharge during the entire monitoring period. Samples shall be taken after final treatment at the outfall.

Table 1-A-1 Continued- Effluent Limitations and Monitoring Requirements. Source: After USEPA

Facility Operation

Construction of the eastern facility was completed in 2013 and operations were commenced. The facility as shown in the flow diagram in Figure C-3 included a truck unloading station which drained via gravity to two 10,000 bbl. HDPE (high density polyethylene) lined sedimentation basins. These basins were designed to allow for the settling of any large particles within the water. While the facility was not designed to remove or treat oil or free-floating hydrocarbons as this is not normally encountered in Fayetteville Shale water, they were additionally designed to trap any free-floating oil that may have been in trucks that were utilized for other purposes. The water then flowed via gravity into a single 250,000 bbl. HDPE lined basin that was equipped with two aerators to allow for limited biological treatment of the water for the removal of ammonia and methanol. The water was then pumped as required to two 400 bbl. vertical tanks where it could be loaded on trucks for reuse in Southwestern Energy's operations or it would flow by gravity to another 400 bbl. vertical tank that feeds the treatment system.

From the treatment feed tank, the water was dosed with coagulant and treated in an Induced Gas Flotation (IGF) unit to further enhance the removal of suspended solids. Then the water would be pumped to one of two Mechanical Vapor Recompression (MVR) units. The MVRs were designed to desalinate the water. The concentrated brine produced by the MVRs was pumped to a tank for either reuse in Southwestern Energy's operations or eventually to be hauled via truck to a SWD for disposal. The distilled water from the MVRs was pumped into one of three verification tanks. These tanks, while not required by ADEQ, were installed to allow Southwestern Energy to test the treated water to ensure it met discharge requirements before actual discharge. If the water failed to meet the discharge limits, it was cycled back to the impoundment to be retreated. See the attached flow diagram of the treatment system below for reference.

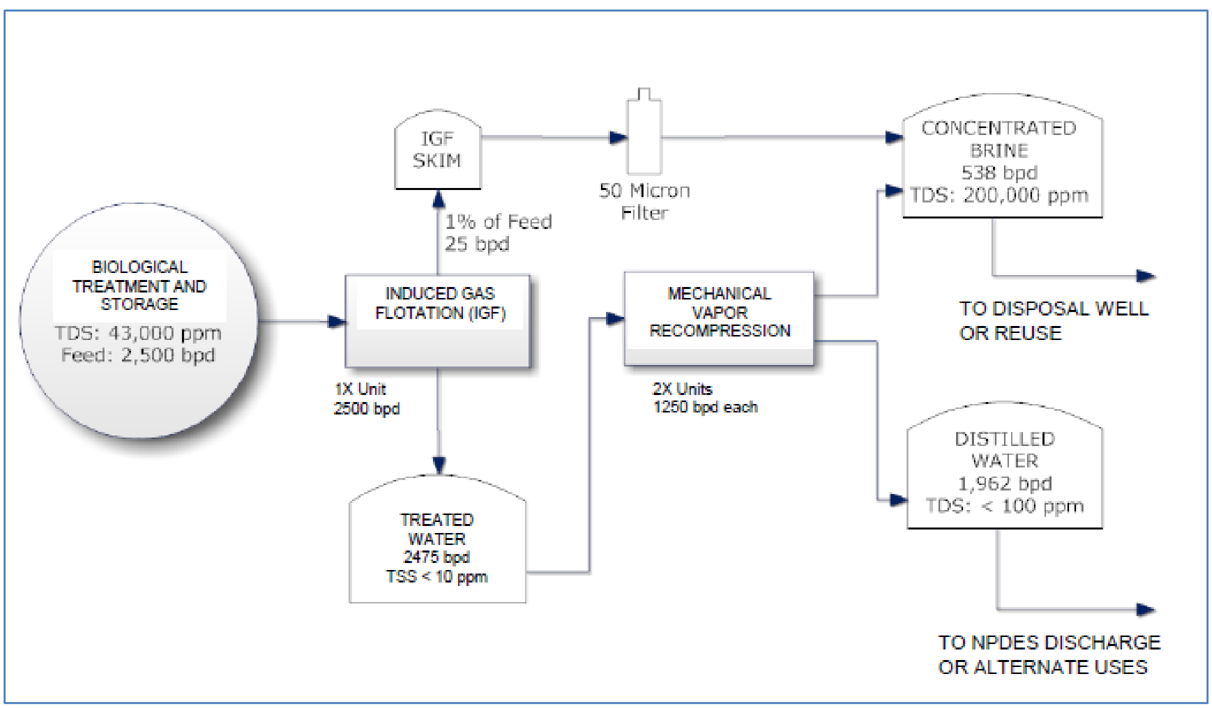


Figure 1-A-3 – Flow Diagram of Treatment Facility   Source: Southwestern Energy

One complicating factor was that based on the facility's location, the water was discharged into a small water body that resulted in a requirement to pass the Whole Effluent Toxicity (WET) test at 100%

discharge, not allowing for any dilution impact of the receiving water body as is often allowed when discharging into larger water bodies. As the water was distilled, it had no minerals in it that are essential for the invertebrates (Ceriodaphnia) in the WET test to survive and reproduce. As a result, a remineralization step was added. The remineralized water met the discharge limits of the NPDES permit, and allowed the invertebrates to survive and reproduce, thereby satisfying WET test requirements.

Subsequently after operations commenced, a need arose in Southwestern Energy's operations for distilled water in the summer months. Southwestern diverted the distilled water into storage tanks on site for use in its operations.

Current Status

Due to changes in natural gas prices combined with the relatively high cost of operating the facility in comparison with Southwestern Energy's direct reuse of the water, the facility was shut down in 2016. The second facility was not fully completed. However, Southwestern Energy is currently piloting a system that utilizes reverse osmosis for desalination at a much lower cost than the MVR system previously deployed. If successful, Southwestern Energy will work with ADEQ to modify the facility's permit for the new treatment system and look to resume treatment and discharge of water.

One of the key lessons that can be learned from Southwestern Energy's efforts in the Fayetteville Shale are that there are ways to permit the treatment and surface discharge of water from oil and gas operations even east of the 98th Meridian under the NPDES program. It is recommended that both the facility operator and the state agencies begin dialog early and work together to establish treatment and effluent requirements so that the facility can be properly designed. Open sharing of information about the water and the treatment technologies is important to help establish discharge limits that are practical while still protecting human health and the environment. Additionally, the location of the facilities can have a significant impact on discharge limits. Early discussions between the operator and the agency can help to identify such issues early on and help to find solutions to unexpected issues that may arise. Note that modifications had to be made to the initial facility design, and ADEQ was willing to work with Southwestern Energy to allow those modifications.

APPENDIX 1-B: 2003 General Accounting Office (GAO) Report

A 2003 report by the General Accounting Office (GAO)[215] describes water rights as follows:

> "The variety of state water laws relating to the allocation and use of water can generally be traced to two basic doctrines: the riparian doctrine and the prior appropriation doctrine. Under the riparian doctrine, water rights are linked to land ownership—owners of land bordering a waterway have a right to use the water that flows past the land for any reasonable purpose. Landowners may, at any time, use water flowing past the land even if they have never done so before; all landowners have an equal right to use the water and no one gains a greater right through prior use. In contrast, the prior appropriation doctrine does not link water rights with land ownership. Water rights are instead linked to priority and beneficial water use—parties who obtain water rights first generally have seniority for the use of water over those who obtain rights later, and rights holders must put the water to beneficial use or abandon their right to use the water. Simply put, "first in time, first in right" and "use it or lose it." When there is a water shortage, under the riparian doctrine all water users share the shortage in proportion to their rights, while under the prior appropriation doctrine, shortages fall on those who last obtained a legal right to use the water.
>
> For managing surface-water allocation and use, Eastern states generally adhere to riparian doctrine principles and Western states generally adhere to prior appropriation doctrine principles. We obtained information on the water management doctrines of 47 states from our 50-state Web-based survey of state water managers. As shown in figure 5 [Figure 1-B-1 in this appendix], 16 states follow either common-law riparian or regulated riparian (state permitted) doctrine, 15 states follow prior appropriation doctrine, 13 states follow other doctrines, and 2 states do not regulate surface-water allocation.
>
> Special rules apply to allocating ground-water rights, but most state approaches reflect the principals of prior appropriation or riparian doctrines, with some modifications that recognize the unique nature of ground-water. As shown in figure 6, [Figure 1-B-2 in this appendix], 18 states follow the riparian-derived doctrine of reasonable use; 12 states follow the prior appropriation doctrine; 13 states follow other approaches, such as granting rights to water beneath property to the landowners (absolute ownership) or dividing rights among landowners based on acreage (correlative rights); and 3 states do not regulate ground-water allocation."

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[215] In 2003 the agency was known as the General Accounting Office. Since then the title has changed to the Government Accountability Office.

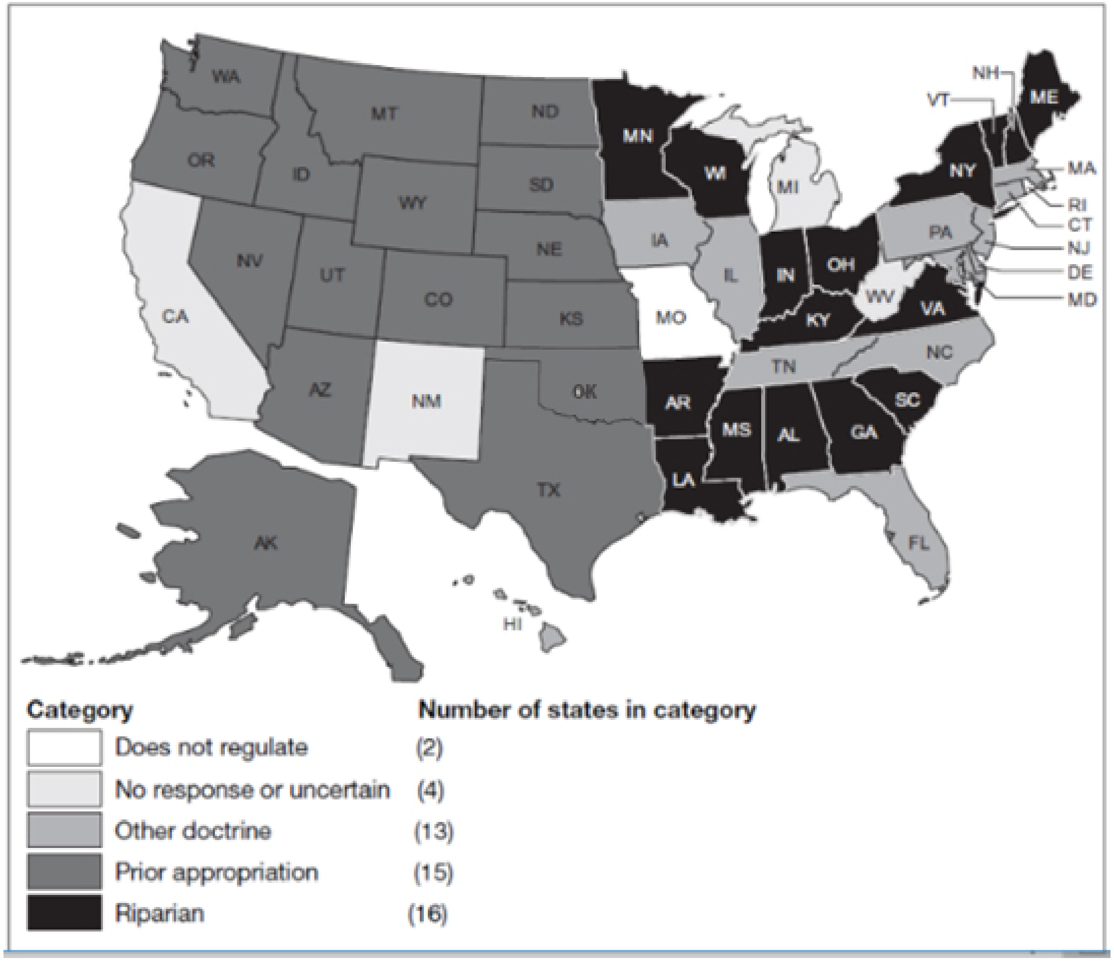

Figure 1-B-1. State Water Rights Approaches for Allocating Surface Water Resources

Source: U.S. General Accounting Office (GAO), 2003, Freshwater Supply — States' Views of How Federal Agencies Could Help Them Meet the Challenges of Expected Shortages, Washington, DC. Available at http://www.gao.gov/new.items/d03514.pdf.

NOTE: Oklahoma has been updated from the original map to show that it is a prior appropriation state.

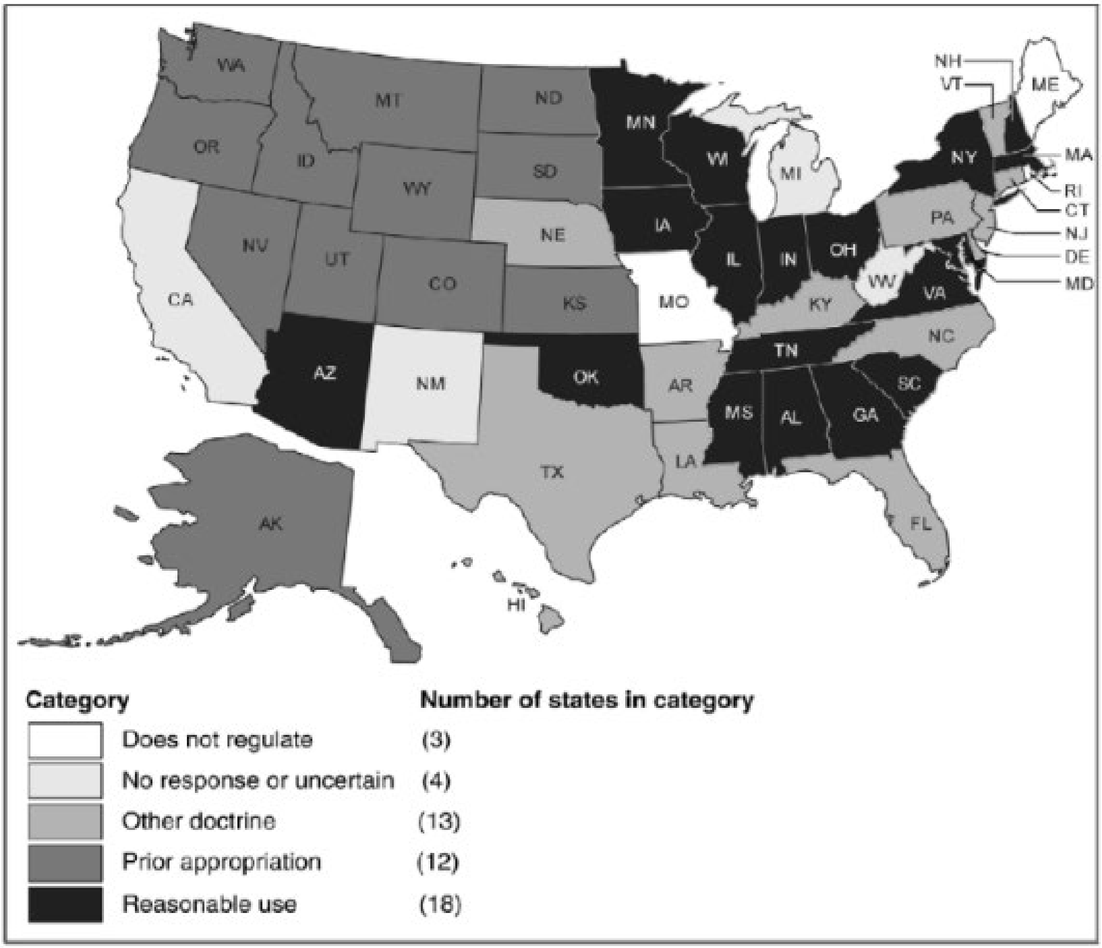

Figure 1-B-2. State Water Rights Approaches for Allocating Ground Water Resources

Source: U.S. General Accounting Office (GAO), 2003, Freshwater Supply — States' Views of How Federal Agencies Could Help Them Meet the Challenges of Expected Shortages, Washington, DC. Available at http://www.gao.gov/new.items/d03514.pdf

NOTE: Figures 1-B-1 and 1-B-2 are the latest maps available from the GAO. To obtain the latest information concerning a state's water rights, contact the appropriate agencies in the state of interest.

APPENDIX 1-C: Changes to Texas Regulations on Recycling of Produced Water

Presented at the January 2014 GWPC UIC Conference

Railroad Commission of Texas

Recycling O&G Fluids in Texas

Leslie Savage
Chief Geologist, Oil and Gas Division

RECYCLING AMENDMENTS

- Authorize certain on-lease, non-commercial recycling of hydraulic fracturing flowback fluid, with conditions
- Clarify permitting requirements for commercial or centralized recycling of hydraulic fracturing flowback fluid

Rule 8 Background

- Subsections
  - (b) No Pollution
  - (d) Pollution Control
    - Prohibited / Authorized Disposal
    - Prohibited / Authorized Pits
    - **Prohibited / Authorized Recycling**

3

RULE 8: New Authorized Fluid Recycling

Non-Commercial Fluid Recycling –

The recycling of fluid produced from an oil or gas well, including produced formation fluid, workover fluid, and completion fluid, including fluids produced from the hydraulic fracturing process on an existing designated lease or drilling unit associated with a commission-issued drilling permit or upon land leased/owned by the operator for the purposes of operation of a non-commercial disposal well..., where the operator of the lease, drilling unit, or non-commercial disposal or injection well treats, or contracts with a person for the treatment of, the fluid and may accept such fluid from other leases and or operators.

4

RULE 8: What's Recycling?

Recycle- "To process and/or use or re-use oil and gas wastes as a product for which there is a legitimate commercial use and the actual use of the recyclable product." As defined in this subsection, does not include injection pursuant to an enhanced recovery injection well permit.

Legitimate commercial use--Use or reuse of a recyclable product as authorized or defined in a permit:

(A) as an effective substitute for a commercial product or as an ingredient to make a commercial product; or

(B) as a replacement for a product or material that otherwise would have been purchased; and

(C) in a manner that does not constitute disposal.

5

RULE 8: Authorized Reuse

- Reuse as makeup water, or other use in the wellbore of an oil, gas or geothermal well.
- Reuse in any other manner pursuant to a permit issued by another state or federal agency
- Any reuse if the water is distilled
- **No discharge to waters of the state without permit**

6

Rule 8 – Authorized Pits

- Authorized pits include:
  - **Non-commercial Fluid Recycling Pit**
  - Reserve pit
  - Completion/Workover pit *(including frac flow-back)*
  - Mud circulation pit
  - Fresh makeup water pit
- Authorized pits must be closed in accordance with Rule 8
- §3.8(b) "No pollution" **ALWAYS** applies.

7

RULE 8 - Recycling

Authorized

Non-Commercial Fluid Recycling Pit - Pit … for the storage of fluid for the purpose of Non-Commercial Fluid Recycling or for the storage of treated fluid.

Provided that…

8

Rule 8 - Recycling

- Authorizes Non-Commercial Fluid Recycling Pits to store fluid from an oil or gas well that will be treated and reused if:
  - Pit is lined
  - Liner has a hydraulic conductivity of $1x10^{-7}$ cm/s or less
  - Two feet of freeboard is maintained
  - Pit is emptied and inspected annually or it has a leak detection system that is monitored monthly
  - District registration and landowner permission

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Rule 8 - Recycling

- If a pit is not authorized by Rule 8, an application must be filed with, and approved by, the Commission before use of the pit can begin.

10

Rule 8 - Recycling

- No authorized pits may be placed in the 100-year flood plain
  - Can be approved by District Director
  - May request hearing if denied

11

NEW COMMERCIAL RECYCLING RULES

CHAPTER 4, SUBCHAPTER B

13

New Chapter 4, Subchapter B Divisions

Six Divisions for Commercial Recycling Rules

1. **General Requirements**
2. On-Lease Solid Waste Recycling
3. Off-Lease or Centralized Solid Waste Recycling
4. Stationary Solid Waste Recycling
5. **Off-Lease Fluid Recycling**
6. **Stationary Fluid Recycling**

14

New Chapter 4, Subchapter B Divisions

Division 1. General; Definitions

Authorizes recycling of fluid received at a commercial disposal well, provided the operator of the well:

treats, or contracts with a person for the treatment of the fluid;

is responsible for all activities, including the recycling, that occurs on the lease;

has obtained financial security;

provides written notification to RRC 7 days before recycling operations are expected to begin and includes information on how fluids will be controlled and contained during recycling operations; and

provides written notification to RRC within 7 days of concluding recycling operations.

15

New Chapter 4, Subchapter B Divisions

Division 1. General; Definitions (cont'd)

- Requires a permit
- Must use a permitted Oil and Gas Waste Hauler

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New Chapter 4, Subchapter B Divisions

Division 1. General; Definitions (cont'd)

General Standards for Permit Issuance

Facility may only receive, store, handle, treat, or recycle waste:

(1) under the jurisdiction of RRC;

(2) that is not a hazardous waste; and

(3) that is not oil and gas NORM waste.

Permit may be issued only if RRC determines that:

(1) the storage, handling, treatment, and/or recycling of oil and gas wastes and other substances and materials will not result in the waste of oil, gas, or geothermal resources, the pollution of surface or subsurface water, a threat to public health and safety; and

(2) the recyclable product can meet engineering and environmental standards RRC establishes in the permit or in this subchapter for its intended use.

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New Chapter 4, Subchapter B Divisions

Division 1. General; Definitions (cont'd)

General Standards for Permit Issuance

Permit will prohibit speculative waste accumulation

Engineering/geological work products must be signed by their respective Texas-registered professionals

All oil and gas waste and recyclable product must be stored in lined permitted pits or above-ground storage tanks.

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New Chapter 4, Subchapter B Divisions

Division 5. Off-lease commercial fluid recycling facility--A commercial recycling facility that is *capable of being moved from one location to another, but which is generally in operation in one location for a period of time longer than one year, but less than two years* that recycles wellbore fluid produced from an oil or gas well, including produced formation fluid, workover fluid, and completion fluid, including fluids produced from the hydraulic fracturing process.

Division 6. Stationary commercial recycling facility - A commercial recycling facility *in an immobile, fixed location for a period of greater than two years* that recycles solid oil and gas waste or wellbore fluid produced from an oil or gas well, including produced formation fluid, workover fluid, and completion fluid, including fluids produced from the hydraulic fracturing process.

Division 5. Off-Lease Commercial Recycling of Fluid

- Application
- Minimum Engineering and Geologic Information
- Minimum Siting Information
- Minimum Real Property Information.
- Minimum Design and Construction Information
- Minimum Operating Information
- Minimum Monitoring Information
- Minimum Closure Information
- Notice (surface owner, adjoining surface owners, city/county clerk)

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Division 5. Off-Lease Commercial Recycling of Fluid

- General Permit Provisions
- Minimum Permit Provisions for Siting
  - Only if facility is to be located in an area where there is no unreasonable risk of pollution or threat to public health or safety
  - Cannot be located within a 100-year flood plain, in a streambed, or in a sensitive area
  - Cannot be located within 150 feet of surface water or public, domestic, or irrigation water wells.
  - Other factors include volume and characteristics of the waste; proximity to surface water; depth to and quality of the shallowest groundwater; distance to the nearest property line or public road; proximity to coastal natural resources, sensitive areas, or water supplies, and/or public, domestic, or irrigation water wells.

Division 5. Off-Lease Commercial Recycling of Fluid

- Minimum Permit Provisions for Design and Construction
  - All areas must minimize contact of oil and gas waste and partially recycled waste with the ground surface, and prevent pollution
  - Monitor wells
- Minimum Permit Provisions for Operations
  - Only wastes and other materials authorized by permit may be received, permittee must test incoming oil and gas waste and keep records of amounts and sources of incoming wastes; and
  - Processing operation and resulting recyclable product must meet environmental and engineering standards established in the permit
  - Requirements, including limits on the volumes of oil and gas waste, partially treated waste, and recyclable product stored at the facility, to ensure no speculative accumulation

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Division 5. Off-Lease Commercial Recycling of Fluid

- Minimum Permit Provisions for Monitoring
  - Permit for use of the treated fluid for any purpose other than re-use as makeup water for hydraulic fracturing fluids to be used in other wells may require laboratory testing.
  - A permit that requires laboratory testing shall require that the permittee use an independent third party laboratory to analyze a minimum standard volume of partially treated waste for parameters established in this division or in a permit issued by RRC
- Minimum Permit Provisions for Closure

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DIVISION 6. Stationary Commercial Fluid Recycling

- Requirements generally the same, except for
  - Both personal and published notice - Must publish notice of the application in a newspaper of general circulation in the county at least once each week for two consecutive weeks.
  - More intensive Staff review of application.
  - Permit term of not more than 5 years.

SUMMARY

- Water quality standards dictated by reuse
- Location and Duration
  - Non-Commercial Fluid Recycling Authorized by Rule 8
  - Division 5: Off-lease for up to 2 years
  - Division 6: Stationary for 2 or more
- Site and Property Information, monitor wells and financial security required for Off-lease and Stationary recycling facilities
- Notice
  - Surface and Adjacent owners for Off-lease Landowners and
  - published notice for Stationary

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APPENDIX 1-D: A Brief History Behind the Recycling Rule in New Mexico

EJS Graham
University of New Mexico Center for Water and the Environment
September 27, 2018

A series of droughts in New Mexico, particularly affecting southeastern NM, along with increasing oil and gas activity in the Delaware and Permian Basins including hydraulic fracturing (HF) operations, provided the impetus for development of the recycling rules for produced water in New Mexico. HF uses large quantities of water for fracturing operations (up to ~1MG per well). When HF was advancing in the early to mid-2000's, fresh water was the standard substrate for HF fluids. As HF technology developed, water with higher amounts of dissolved salts was found to be acceptable for use. Recycled produced water thus became more feasible for use in arid regions where fresh water was becoming more expensive. In addition, the transportation costs, and negative impacts on regional roadways from increased trucking, made fresh water less appealing and less cost effective.

Governor Susana Martinez declared a drought declaration for the entire state of New Mexico in 2012. Secretary David Martin of the New Mexico Energy, Minerals, and Natural Resources Department was charged with leading Drought Task Force efforts on the treatment and use of brackish and produced waters, to augment fresh water supplies. He created committees to look at both use and reuse of these waters. Produced water recycling was recommended by the group to be a viable option to help reduce fresh water use within the oil and gas industry. Secretary Martin then asked the Oil Conservation Division to review and draft a rule that would promote recycling and would protect fresh water and the environment.

OCD staff and members of the Produced Water Working Group met several times from 2013 to 2015 and drafted an order to repeal and replace Title 19, Chapter 15, Part 34 of the New Mexico Administrative Code (NMAC). The Oil Conservation Commission received the application from the New Mexico Oil and Gas Association, conducted hearings, reviewed and revised the rule and passed a final order which became effective on March 31, 2015.

The purpose of the recycling rules within the disposition code are to protect fresh water and encourage recycling of produced water (*see* NMAC 19.15.34.7 (A)). A series of hearings and a "road show" of listening sessions were held prior to the Oil Conservation Commission hearing where the rule was publicly aired and subsequently adopted.

New Mexico administrative code allows for "disposition by use" of produced water[216]. The rule objective is to protect against contamination of fresh water and to establish procedures for handling of

[216] New Mexico Administrative Code (NMAC) Title 19, Chapter 15, Part 34, Produced Water, Drilling Fluids, and Liquid Oil Field Waste (http://164.64.110.134/parts/title19/19.015.0034.html)

produced water[217]. This rule not only includes listed uses such as drilling, completion, producing, secondary recovery, pressure maintenance or plugging of wells, but also includes other disposition uses such as industrial use or electricity generation. The rule does not specifically exclude dispositions by use, but disposition uses must be approved by the appropriate district division office of OCD.

The recycling rules include the definitions of containments, construction requirements, recordkeeping for operations, and operational rules for use. OCD reviews all applications and ensures that facilities are properly constructed and maintained. OCD thoroughly reviews all required lined leak detection systems. OCD also reviews and ensures all facilities include provisions to prevent run-on from storm water.

[217] "OBJECTIVE: To encourage the recycling, re-use or disposition of produced water by use in a manner that will afford reasonable protection against contamination of fresh water and establish procedures by which persons may transport and dispose of produced water, drilling fluids and other liquid oil field waste." [19.15.34.6 NMAC - Rp, 19.15.34.6 NMAC, 3/31/15]

APPENDIX 1-E: Produced Water Related Resources

Comparative Information on State Regulations

Listed below are several resources that provide general information on state produced water regulations. In addition, internet searches can be used to locate other documents that look at the oil and gas or underground injection regulations for individual states or regions.

1. State Oil and Natural Gas Regulations Designed to Protect Water Resources, Third Edition – This 2017 report by GWPC updates earlier 2009 and 2014 reports on state oil and gas regulations. It includes a wide array of information on regulations that protect water resources but does not focus on produced water management specifically. There is a great deal of information about which state agencies have authority to oversee water protection programs. http://www.gwpc.org/sites/default/files/State%20Regulations%20Report%202017%20Final.pdf
2. *Produced Water Management Information System (PWMIS)* – PWMIS was created by Argonne National Laboratory in 2007 for the U.S. Department of Energy's (DOE's) National Energy Technology Laboratory (NETL). https://www.netl.doe.gov/research/coal/crosscutting/pwmis/intro. PWMIS featured three separate modules
    - *Technology Assessment Module* – basic information about many types of treatment technologies and management practices used for produced water
    - *Technology Identification Module* – an interactive tool for determining optimal practices for a given geographical setting
    - *Regulatory Module* – online summary of state and federal produced water requirements with links to those regulations

Initially Argonne hosted and maintained the details and links on PWMIS. A few years later, NETL moved PWMIS to its website https://www.netl.doe.gov/research/coal/crosscutting/pwmis/fed-state-regulations. The regulatory module information has not been maintained or updated since 2010. Although many of the links are no longer active, and other changes to agency names or regulatory codification have taken place, this site can serve as a resource.

3. *States, Territories and Tribes Responsible for the UIC Program.* This .pdf file maintained by the USEPA contains a listing of the states, territories and tribes that have primary enforcement authority (primacy) over the UIC program on a well class by well class basis. https://www.epa.gov/sites/production/files/2017-08/documents/primacy_status_revised_aug_8_2017_508c_1.pdf NOTE: This listing does not include the recently approved primacy programs in Kentucky (Class II) or North Dakota (Class VI)
4. *U.S. Produced Water Volumes and Management Practices in 2012* – This report was prepared by Veil Environmental, LLC for GWPC in 2015 as an update to a 2009 report. It includes summaries of how much produced water was generated from all wells in 2012 for each oil and gas producing

state. A summary describing how that volume of produced water was managed is also provided. Although this report does not go into the details of specific regulations, it does provide guidance on how produced water was managed and which agency had regulatory responsibility for each of the management programs. http://www.veilenvironmental.com/publications/pw/final_report_CO_note.pdf.

5. *Review of State Oil and Natural Gas Exploration, Development, and Production (E&P) Solid Waste Management Regulations*. This 2014 report summarizes investigations made by EPA into state oil and gas agency regulations concerning E&P wastes during 2013. Content focuses on regulations related to waste pits at hydraulic fracturing sites. While not directly related to produced water, it provides information on state regulations dealing with E&P wastes. https://www.USEPA.gov/sites/production/files/2016-04/documents/state_summaries_040114.pdf.
6. *"The Regulatory Framework Surrounding Produced Water in New Mexico and Impacts on Potential Use".* This report was prepared by Enid J. Sullivan Graham, Ph.D under the New Mexico Office of the Secretary, Energy Minerals and Natural Resources Department and Los Alamos National Laboratory, Los Alamos, New Mexico and Kwabena Addae Sarpong, Graduate Research Assistant the Water Resources Research Institute at New Mexico State University. It describes the pertinent regulations in New Mexico within the jurisdiction of the NM Oil Conservation Division (NMOCD), the NM Office of the State Engineer (NMOSE), and the NM Environment Department (NMED). It includes case studies from New Mexico, Wyoming, California and Colorado, provides hypothetical scenarios relative to produced water treatment and use processes and identifies gaps in the regulatory framework. https://nmwrri.nmsu.edu/wp-content/uploads/ProducedWater-Reports/Reports/Sullivan-Graham%20and%20Sarpong%202016%20-%20The%20Regulatory%20Framework%20Surrounding%20Produced%20Water%20in%20New%20Mexico%20and%20Impacts%20on%20Potential%20Use.pdf

Best Practices and Guidance Documents

In addition to the resources listed below, many other reports, articles, and presentations are available addressing best practices, usually for specific projects or situations.

Industry Documents

Each year API works with leading industry experts to maintain an inventory of over 600 standards and recommended practices. API's 2017 catalog of publications and standards can be found at http://www.api.org/~/media/Files/Publications/Catalog/2017_catalog/API_2017_Catalog.pdf. Some documents relevant to produced water are:

1. ANSI/API RP 100-1 -- Well Integrity and Fracture Containment, 1st Edition, October 2015. This Recommended Practice highlights practices for onshore well construction and fracture stimulation design and execution relating to well integrity and fracturing containment. It also identifies actions to protect and isolate useable quality groundwater through application of appropriate barriers and controlled fracture design and execution practices.

2. ANSI/API RP 100-2 -- Managing Environmental Aspects Associated with Exploration and Production Operations Including Hydraulic Fracturing, 1st Edition, August 2015. These documents include topics on managing environmental aspects during site planning; site selection; logistics; mobilization; rig up and demobilization; and stimulation operations.
3. ANSI/API Bulletin 100-3 -- Community Engagement Guidelines, 1st Edition, July 2014. This bulletin outlines what local communities and other key stakeholders can expect from operations.
4. API Standard 65 Part 2 – Isolating Potential Flow Zones During Well Construction, 2nd Edition, December 2010. This API standard help ensure the well is properly designed and constructed to contain the hydrocarbons through the well bore and isolate them from groundwater aquifers. It also includes information on industry cementing practices.
5. API RP 51R – Environmental Protection for Onshore Oil and Gas Production Operations and Leases, 1st Edition, July 2009. This recommended practice provides environmentally sound practices for domestic onshore oil and gas production operations, including fracturing.
6. Guidelines for Commercial Exploration and Production Waste Management, March 2001. These guidelines are intended to identify design, construction, and operational options that may be used, depending on site-specific conditions, at facilities to protect human health and the environment.

NOTE: The documents listed above are available free of charge from API and can be found at https://www.api.org/oil-and-natural-gas/wells-to-consumer/exploration-and-production/hydraulic-fracturing. Those listed below are available for purchase from API.

1. API E5 Environmental Guidance Document: Waste Management in Exploration and Production Operations, 2nd Edition, February 1997. This document provides guidance for minimizing the direct and indirect environmental impacts of solid wastes originating from typical exploration and production (E&P) activities.
2. RP 45 Recommended Practice for Analysis of Oilfield Waters., 3rd Edition, August 1998. This document is directed toward the determination of dissolved and dispersed components in oilfield waters (produced water, injected water, aqueous workover fluids, and stimulation fluids).

Documents by Federal Agencies

The Department of the Interior is home to several agencies with an interest in oil and gas activities, including produced water.

The Bureau of Land Management (BLM) manages the Federal government's onshore minerals, including about 700 million acres of land held by the BLM, U.S. Forest Service, other Federal agencies, and other surface owners. The Agency also manages some aspects of the oil and gas development for Indian tribes. BLM published *"Surface Operating Standards and Guidelines for Oil and Gas Exploration and Development"* (commonly referred to as the Gold Book) to provide operators with information on the requirements for obtaining permit approval and conducting environmentally responsible oil and gas operations on federal lands and on private surface over federal minerals (split-estate).

The Bureau of Reclamation (BOR) has a mission to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public. The Technical Service Center, Environmental Services Division, Water Treatment Engineering and Research Group for the BOR has published a series of produced water studies, including:

1. Guidance to Evaluate Water Use and Production in the Oil and Gas Industry, March 2014. This guidance's objective is to present a standard method of water assessment to determine regional water use and production in the oil and gas industry.
2. Oil and Gas Produced Water Management and Beneficial Use in the Western United States, September 2011. This guidance describes the water quality characteristics of produced water, performed an assessment of water quality in terms of geographic location and water quality criteria of potential beneficial uses, identified appropriate treatment technologies for produced water, and described practical beneficial uses of produced water.
3. Guidance for the Evaluation of Produced Water as an Alternative Water Supply, April 2013. This document discusses potential "new water" sources, identifies location, quantity, quality, and accessibility of water supply and demand and determines risk of water shortages and potential conflicts.
4. Produced Water in the Western United States: Geographical Distribution, Occurrence, and Composition, 2008. This paper aims to illustrate the concentration ranges for specific contaminants and the estimated quantity of coproduced water in the Western United States.

Other Resources

The Inter-Mountain Oil and Gas BMP Project website was developed at the University of Colorado (CU) Law School's Getches-Wilkinson Center for Natural Resources, Energy and the Environment (formerly Natural Resources Law Center). The project is maintained through grants to CU and its partners. The focus of the website is a searchable database addressing surface resources affected by oil and gas development. The database includes both mandatory and voluntary BMPs currently in use or recommended for responsible resource management in the states of Colorado, Montana, New Mexico, Utah, and Wyoming.

APPENDIX 1-F: Changes in Pennsylvania Marcellus Shale Water Management Practices over Time

The Marcellus Shale underlies much of Pennsylvania and portions of New York, Ohio, and West Virginia (Figure 1-F-1). These states have a long history of oil and gas development (e.g., the first U.S. oil well was in Titusville, PA in 1859, and the first U.S. gas well was in Fredonia, NY in 1825) through conventional wells. The Marcellus Shale has long been known to hold hydrocarbon resources, but using conventional drilling and completion technologies, those wells were not cost-effective. Following successful production of unconventional shale wells in Texas when directional drilling and hydraulic fracturing technologies were used together, commercial development in the Marcellus Shale region started about 2005 and quickly spread as the wells proved to be profitable.

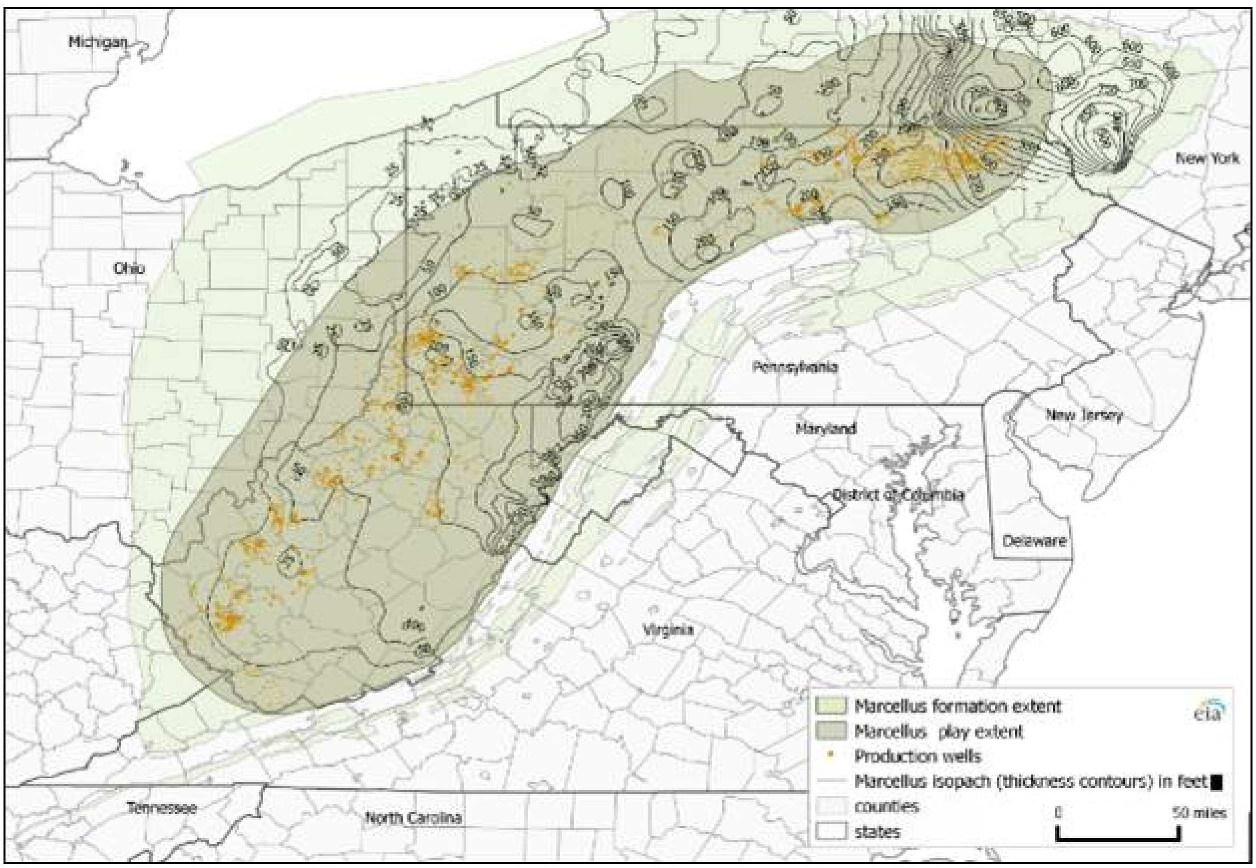

Figure 1-F-1. Map of Marcellus Shale Formation and Play Source: DOE, Energy Information Administration. See https://www.eia.gov/todayinenergy/detail.php?id=20612.

Management of produced water can be done in various ways. As companies review their water management options, they look at cost, regulatory acceptability, sustainability, and physical practicality of each option. Typically, they choose one option as a first choice and may include several other options as alternates.

The companies that began drilling wells in the Marcellus Shale had prior experience in Texas, where a large percentage of the produced water was injected into disposal wells. In that area, disposal wells were readily available close to the production areas. The cost of trucking and disposing the produced water was modest.

As those companies moved into Pennsylvania, they anticipated that they would manage produced water in the same manner. They quickly learned that only a few disposal wells had ever been permitted in Pennsylvania, and that UIC wells were permitted by the Region 3 Office of EPA rather than through the Pennsylvania Department of Environmental Protection (PADEP), the agency that regulates oil and gas activities and water activities in the state. PA DEP issued a deep well permit and regulate surface operations. The companies' early efforts to site and permit new injection wells were not highly successful. EPA's UIC permits, when available, offered low daily injection volume limits, and the geological formations near to the Marcellus Shale producing areas were unable to accept large volumes of injected water as was available in Texas and other basins.

In the Marcellus region, the initial preferred option (inject into disposal wells located nearby) was not a realistic choice. Companies were forced to evaluate various other water management choices such as:

- Haul the water to a disposal well in Ohio
- Haul to a nearby industrial wastewater treatment facility
- Haul to a nearby municipal wastewater treatment plant.

None of these options were ideal and are discussed below.

Ohio Disposal Wells

A 2010 report prepared by Argonne National Laboratory for the USDOE (Veil 2010)[1] describes water management practices in the Marcellus Shale at that time. The report noted that numerous commercial disposal wells operated in 15 Ohio counties, nearly all in the eastern portion of the state that abuts Pennsylvania. During 2009, approximately 4.5 million bbl. of gas production produced water was injected into these wells. Some of this produced water came from wells in Ohio and some from wells in Pennsylvania.

In 2017, Ohio UIC wells injected 18.2 million barrels of produced water from out-of-state, primarily from Pennsylvania and West Virginia, accounting for approximately 48 percent of all produced water disposed by injection during 2017. The cost for disposing water at the Ohio wells was not high (<$3/bbl.), but the cost to haul the water for 6-8 hours, wait to unload, then drive home, was extremely high. The standard rule of thumb for trucking cost is roughly $1/bbl./hour. There will be regional variation around those costs, in part due to competition. When disposal fees were combined with transportation costs, the total cost was often $15/bbl. to $20/bbl. In 2017, the UIC disposal method accounted for disposal of about 5.8% of the total produced fluids from unconventional wells in Pennsylvania.

Industrial Wastewater Treatment Plants and Municipal Wastewater Treatment Plants

For decades (long before the boom in Marcellus Shale production), natural gas has been produced from shallow gas wells in Pennsylvania. To manage the relatively low volume of produced water from these wells, a network of industrial wastewater treatment plants was established in Pennsylvania. These plants were designed to remove metals from the wastewater and discharge a clean brine solution to local streams under the conditions of an NPDES permit issued by the PADEP. Veil (2010) provides information about those plants, including descriptions of site visits at four plants. In 2017, only 0.0335% of produced fluids from unconventional wells in Pennsylvania were disposed of by industrial wastewater treatment plants with NPDES discharges.

In addition, several municipal wastewater treatment plants (often called publicly owned treatment works or POTWs) accepted limited volumes of natural gas wastewater that was blended with the incoming sewage before treatment. The POTWs could provide dilution and settling, but the treatment processes included in most POTWs were not designed to remove metals or TDS.

Veil (2010) reports that 15 POTWs were receiving oil and gas water in 2010 or had received it in the past. Many of those POTWs had conditions in their NPDES permits requiring that the volume of wastewater from oil and gas sources may not exceed 1% of the average daily flow.

Provided the total produced water volume managed by these plants remained low, the surface water bodies to which they discharged were unlikely to be impacted by the salt content and other constituents in their effluent. However, as the volume of produced water increased, concerns were raised about impacts to the streams. In response to concern over produced water[2] discharges, the PADEP proposed a new strategy that would add discharge standards for oil and gas wastewaters of 500 mg/L for TDS, 250 mg/L for sulfates, 250 mg/L for chlorides, and 10 mg/L for total barium and total strontium. Those discharge regulations were made final in 2010.

After publication of a series of articles by *The New York Times* and EPA's response to those articles, the practice of sending wastewater to either industrial or municipal wastewater treatment plants stopped in April 2011. The PADEP wrote to each natural gas producer in Pennsylvania and strongly encouraged them to discontinue sending natural gas produced water to these treatment plants that were not equipped to handle high-TDS wastewater. The deadline for accomplishing this change was May 19, 2011. Almost overnight, the volume of produced water going to industrial wastewater treatment plants dropped to near zero. Following this shift in water management, the EPA finalized the oil and gas effluent guidelines to preclude the acceptance of oil and gas produced water by POTWs. In 2017, only 77 barrels of produced fluids in Pennsylvania were reported to PA DEP as going to POTWs.

Other Options Not Previously Considered

Beginning in 2009 and 2010, two new wastewater management options were explored. Under the first option, existing industrial treatment plants could be upgraded to include thermal processes to treat water to a higher quality and/or to evaporate the wastewater. Any new planned wastewater treatment facilities would incorporate those technologies. By adding the desalination step in the treatment process, such facilities could apply for NPDES permits or make arrangements to discharge treated wastewater to a POTW.

About this time, several centralized treatment plants opened as new facilities or added more treatment units to older facilities that could desalinate the wastewater. These plants did take over a small market niche, but growth in the sector did not continue.

In 2009-2010, in a search for lower cost water management options, several companies operating in the Pennsylvania portion of the Marcellus Shale began testing the capture of produced water, doing some simple filtration, and blending the resulting water with fresh water to make up frac fluids for new wells. This technology potentially offered cost savings in three ways:

- Avoids transportation costs for hauling to a disposal site
- Avoids payments to a treatment or disposal facility
- Reduces the cost of obtaining fresh water

This was a novel process at the time, because many thought the high concentrations of TDS, metals, and other constituents would interfere with the performance of the frac fluid in the next well, such that the well would have lower gas production than a well fractured using all fresh water.

Range Resources, one of the oil and gas companies leading the experimentation with this new technology, found that frac fluids that include some recycled produced water got production results that were comparable to those fractured with all fresh water. Range Resources had no indication of issues with frac fluid stability, scaling, or downhole bacterial growth. During 2009, Range Resources completed 44 wells and did stimulation jobs involving 364 stages. The total volume of frac fluid used was 158 million gallons, with 28% of the volume made up of produced water from a previous well. The estimated cost savings from avoided disposal fees, less freshwater purchased, and less trucking costs was $3.2 million. The wells that included produced water accounted for 17% of Range Resources' Marcellus wells. Fifty percent of the wells that used produced water were in the company's top 25 producing wells (Gaudlip 2010)[3].

After that process had been demonstrated to make good frac fluids, nearly all the other companies operating in the Pennsylvania portion of the Marcellus Shale switched over to using produced water. Although disposal capacity played a role in this decision, the primary driver was the cost of filtration and produced water use; which was much less costly than any other option.

Table 1-F-1 provides a summary of PADEP data of how Marcellus Shale (unconventional well) produced water was managed in 2009 versus 2013 versus 2017. In 2009, 75% of the produced water was managed by sending it to industrial treatment plants or POTWs for discharge. In 2017, little of the water was managed in that way. In contrast, in 2009, 18% of the produced water were managed by beneficially using it for new drilling or frac fluids. But in 2017, 94% of the produced water were recycled in that way. This change in water management was driven by the non-availability of the originally-preferred management options, and innovative work by some of the companies to develop new approaches. This is an example of how a new management practice developed by one or a few companies rapidly became a best management practice for the entire region.

Management Practice	**Produced Fluids**					
% Managed by This Practice	2009 Volume	%	2013 Volume	%	2017 Volume	%
Industrial Treatment Plant	15,425,235	59.7	267,787.67	1.1	16,882.31	0
POTW	3,844,351	14.9	0.00	0	77.00	0
Injection Well	137,101	0	3,056,521	12	2,933,229.48	5.8
Reuse/Recycle	4,711,742	18.3	20,350,014	86	47,346,303.81	93.8
Other	1,704,011	0.2	571	0	13,233.81	0
Total	25,822,440	100	23,674,999	100	50,457,979.83	100

Table 1-F-1 – Summary of Water Management in the Pennsylvania Portion of the Marcellus Shale, 2009 vs. 2013 vs. 2017. Source: PADEP online databases.

Despite the widespread adoption of produced water use, there is still 6% of the produced fluids volume being sent to various other disposal outlets. One possible reason for this is that it is easier to capture a large volume of produced water that exits a well during the first two weeks then treat it as one batch. It is considerably more complicated to collect the ongoing low volumes of produced water each week from dozens of wells scattered across a large region, transport the water to a central location, hold it there until needed, then treat it.

A second possible explanation is that producers do not drill and hydraulically fracture enough wells in a year or within geographic proximity. Consequently, they may not have a need for the produced water for several weeks. This is an opportunity for companies to work together to ensure a greater use of the produced water in the oil and gas field. The critical issues are storage, primary treatment, and transportation of the fluids where it may be reused in ongoing well development.

A third limitation is the level of treatment needed for limiting chemical parameters of the reused fluids after several recycles. The level of treatment that can be done locally to the hydraulic fracturing operations may inhibit reusing some produced fluids over time.

APPENDIX 2-A: Case Studies of Produced Water Reuse Projects

XTO Energy/ExxonMobil Midland Basin Case Study

Introduction

XTO Energy operates the Midkiff area located approximately 20 miles SSE of Midland, TX. This development area has enough contiguous mineral acreage, with corresponding access to the surface, to develop a comprehensive water management strategy that minimized fresh water use and reduced impacts to the environment. This project was started in 2018 and includes the following facilities.

1. Buried pipelines for moving water throughout the operating area
    a. Purpose: Mitigation of produced water spills from the use of surface pipelines (hard and flexible)
2. Permanent electric pump stations to reduce use of diesel-powered pump systems
3. Brackish water wells for sourced water to reduce requirements for fresh water
4. Treatment systems to recycle and reuse produced water, and to reduce the use of fresh water

Figure 2-A-1: XTO Energy Midkiff area near Midland Texas Photos courtesy of XTO Energy

Shown above is the Midkiff source water pipeline distribution system. It is a buried system of 30" and 36" pipelines and has a total length of 25 miles throughout the operating area. The fluid handled by this pipeline is a mix of brackish, recycled, and fresh water intended to be moved and used in hydraulic fracturing operations.

The photo above is a permanent electric pump station for sourced water movement through the pipeline system. The gray cylinders are 100-micron filters downstream of the pumps and intended to protect the pipeline from solids accumulation in the system. The pumping capacity is up to 75,000 barrels per day.

Risers for the pipeline system used for points of access are shown above. The risers are used for connecting to storage impoundments or for maintenance operations (e.g., pigging the lines). In the future, these riser systems also may be used to efficiently route fluids to hydraulic fracturing jobs, lessening reliance on surface pipelines (hard or flexible) that could be impacted or damaged by other surface operations.

Above is a photo of a typical brackish water well, in this case Santa Rosa well. More than 50 brackish water wells have been drilled for this operating area and can provide over 100,000 barrels per day of water as an alternative to using fresh water.

The Midkiff facility, shown in the photo above, is a produced water treatment plant capable of treating up to 35,000 barrels per day for recycling reuse. This is one of two recycle treatment plants in the Midkiff operating area providing a total of 80,000 barrels per day of treatment capacity. The circular above ground storage tank shown is a 40,000-barrel influent equalization tank used to even out flows through the treatment process given variable flows coming in from tank batteries. The two square impoundments are dual 500,000-barrel (1 million barrels total) impoundments used to stage sourced water for hydraulic fracturing operations. Both are double lined ponds with leak detection and can be used for any type of water available.

Shell Delaware Basin Water Management

Shell Permian Background

Shell started its Permian Basin operations in 2012 with the acquisition of approximately 600,000 net acres from Chesapeake Energy in the Delaware Basin, which is part of the wider Permian Basin, in West Texas (USA). Shell currently has interest in 500,000 acres (260,000 net acres) in the basin.

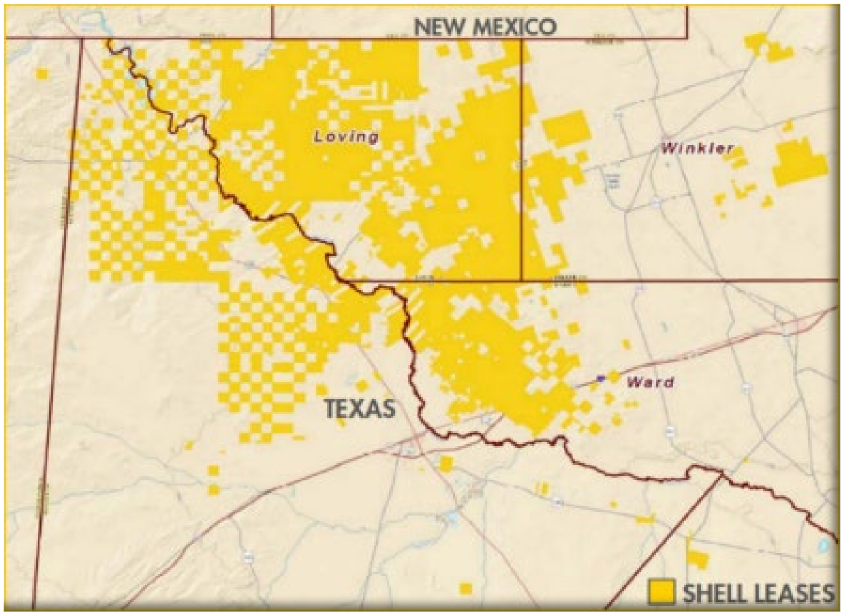

Figure 2-A-2: Source: Shell Capital Markets Day 2016 investor relations presentation. June 7, 2016

Water Sourcing

Shell understands that availability of freshwater is a growing challenge in some areas. Shell manages water sourcing, use and disposal in line with their Onshore Operating Principles and regulatory requirements. Shell has an objective to minimize the use of water in shale operations as well as reduce and ideally eliminate use of freshwater in drilling and hydraulic fracturing operations. In the Delaware Basin, Shell completed a quantitative risk assessment utilizing calibrated numerical simulations to assess the risk to water resources and to understand general availability. The results indicate that brackish groundwater, which is mainly used for shale operations, is plentiful and available near the Pecos River. However, the primary source aquifer is thin or absent in some operating regions. Overall, brackish groundwater should not be overly stressed in their operating area of the Delaware Basin even when using conservative assumptions for all other water demands (i.e., municipal, agricultural, other operator demands, higher well count per section) and with assuming continued drought conditions in the region.

Water Production and Disposal

Hydraulically fractured wells in the Delaware Basin produce approximately 3 – 4 barrels of water per barrel of oil produced. The produced water volumes can be 3 – 7 times the hydraulic fracturing demand. Over the past six years, Shell built significant interconnected water disposal infrastructure (see Figures 2-A-3 and 2-A-4). across their Delaware Basin acreage, which has resulted in the piped produced water disposal increasing from about 25% in 2013 to over 95% today. This, in turn, has resulted in reduced need for water disposal truck hauling and has reduced road safety exposure. Produced water is sourced from SWD surface facilities for the first recycle facility that was built in focused development areas. Plans are also to similarly source produced water for a second recycle facility scheduled to be online late 2018 in another focused development area.

Figure 2-A-3: Water and oil pipelines being jointly constructed in the Delaware Basin.

Figure 2-A-4: Shell's salt water disposal (SWD) surface facility in the Delaware Basin.

Water Recycling

With increased industry activity, water demand has grown across the Permian Basin, highlighting a need for sustainable and economic water management. Prior to their first recycling project, brackish groundwater was transported via an approximate 13 mile (21 km) temporary pipeline for use in hydraulic fracturing operations due to the limited local availability of groundwater. Shell identified an opportunity to replace most of this groundwater supply by recycling produced water near the Johnson Block 53 development area in the Delaware Basin. This recycling allowed for improved operational efficiency, safety, and reduced costs.

In September 2016, the Permian asset commissioned the Johnson Block 53 recycle facility that is now functional and receives produced water from three Salt Water Disposal (SWD) facilities (see Figure 2-A-5). The produced water is transferred from the SWD facilities after standard biocide addition, chemical addition, gravity separation and filtration, and prior to the injection well pumps. Produced water recycle impoundments are equipped with oil booms to collect and remove any floating oil and are also covered with netting to prevent birds from entering/contacting the impoundments. Aerators are installed and operated to mitigate odors and sulfur reducing bacterial growth by keeping the water oxygenated.

Figure 2-A-5: Shell Johnson Block 53 Recycle Facility in the Delaware Basin.

The combined total capacity of recycled produced water storage is approximately 700,000 barrels, and brackish groundwater storage is approximately 30,000 barrels. The three SWD facilities have the capacity to supply up to approximately 70,000 barrels per day of produced water for recycle. Currently, in this area, approximately 60% of water used in hydraulic fracturing is recycled produced water (the remaining 40% is brackish groundwater) and Shell plans to increase the recycle water percentage in this area to approximately 90% in the future.

To read more about Shell's water management practices visit the Shell "Onshore Operating Principles" website.[218]

218 https://www.shell.com/energy-and-innovation/natural-gas/tight-and-shale-gas/shells-principles-for-producing-tight-shale-oil-and-gas/_jcr_content/par/textimage.stream/1487673082490/1966b9f863bcd783472b75bce684ab7d190e6429226d684196aa8ddb7dbaa9d3/shell-onshore-operating-principles-for-tight-sand-or-shale-oil-and-gas.pdf

Newfield Exploration Company STACK Play Water Case Study November 2018

Play Development Is Technology Driven

The following case study briefly summarizes Newfield Exploration Company's (Newfield) water management operations in the STACK oil play of central Oklahoma. Newfield has more than 250,000 net acres of mineral leases in STACK that are mostly contiguous and well suited to water infrastructure investment.

After leasehold drilling was completed, Newfield began a development drilling program which is expected to continue for many years. Newfield's development process constantly leverages new learnings and technologies - leading to continuous engineering improvements and scheduling changes. One example is our hydraulic fracturing (HF) fluid system design that has evolved from slickwater to gel to high viscosity friction reducer (HVFR) systems. Each of these HF fluid system design changes were integral to overall efforts to enhance well performance and lower development costs. Specific to water management, as HF fluid systems change, the water volume and quality needs also change and for this reason, operational control of water management is crucial to Newfield's long-term development for STACK.

Water Resources Available

This portion of Central Oklahoma has an average annual rainfall of approximately 35 inches per year. Two major river systems traverse this area with surface and groundwater rights managed by the state.

Quick Facts Summary	
Location	Kingfisher and Blaine Counties, OK
Hydraulic Fracturing Design	High Viscosity Friction Reducer (HVFR) systems that are customized to accommodate a range of sourced water chemistries
Water Required per New Well Completion	2018 YTD average for a 10,000' lateral is about 450,000 barrels (bbls)
Produced Water Volume Generated	2018 YTD average generated in STACK is about 57,200 barrels per day (bpd)
Produced Water Volume Reused	2018 YTD average treated and reused in STACK is about 21,000 bpd which is 37% of our volume generated
Produced Water Volume Relative to Oil and Gas Production	2018 YTD average is about 0.6 bbls of produced water generated per barrel oil equivalent (BOE) produced in STACK
Typical Produced Water Chemistry	✓ TDS – 40,000 mg/L ✓ Chlorides – 25,000 mg/L ✓ Hardness (as bicarb) – 800 mg/L ✓ Calcium – 1,500 mg/L ✓ Magnesium – 300 mg/L ✓ Sulfate – 700 mg/L ✓ Iron – 5 mg/L ✓ Boron - 50 mg/L
Dominant Modes of Transportation	✓ freshwater – HDPE and layflat ✓ produced water – HDPE and trucks ✓ treated produced water – HDPE and layflat
Storage Capacity	✓ freshwater – 10,000,000 bbls ✓ treated produced water – 5,000,000 bbls
Permanent Water Pipeline System	✓ Over 150 miles of buried 12" SDR7 HDPE ✓ Operating rates up to 100 bpm and pressures up to 200 psi
Disposal Well Capacity	✓ Newfield SWD – 20,000 bpd ✓ 3rd party SWDs – 40,000+ bpd
Treatment and Reuse Capacity	Barton Recycling Facility can deliver 30,000 bpd under normal operations
Driver for Recycling	Reduce our freshwater demand for hydraulic fracturing operations and our SWD capacity needs for disposal
Investment in STACK Water Infrastructure	$90,000,000 to date for all storage, pipelines, recycling, disposal and related facilities
Organizational Structure	Water is managed by a centralized team of engineering and field staff that reports to the VP of Production and Facilities

Fresh groundwater supply is very limited or nonexistent across most of STACK and not considered a significant sourcing option. Potentially significant, but not mapped marginal quality groundwater exists across STACK and is considered brackish or more than 10,000 mg/L total dissolved solids (TDS) that could provide a long-term sourcing solution.

Current Newfield freshwater sourcing is obtained from private rainfall capture and water withdrawal rights from rivers and creeks. Additional sourcing is available from treatment and reuse of our own produced water, also called produced water recycling.

Water Management System and Components

Recycling is part of a comprehensive water management plan where storage and transportation make up the largest portion of our facility needs. In 2012, freshwater storage installations began, in 2013 produced water storage installations began, in 2014 our backbone high density polyethylene (HDPE) pipeline system began, in 2017 our permanent recycling facility was commissioned. This system of storage, transportation, treatment, reuse and disposal is continually being expanded into new development areas of STACK.

Figure 2-A-6 below provides a snapshot of this water system that currently includes more than 150 miles of buried HDPE pipe, over 15,000,000 bbls of storage, disposal capacity over 60,000 bpd and recycling capacity of 30,000 bpd. Figure 2-A-7 below provides a view of the Barton Recycling Facility using traditional oilfield separation and filtration for initial treatment, then adds aeration for oxidation of contaminants and organic removal through bioremediation.

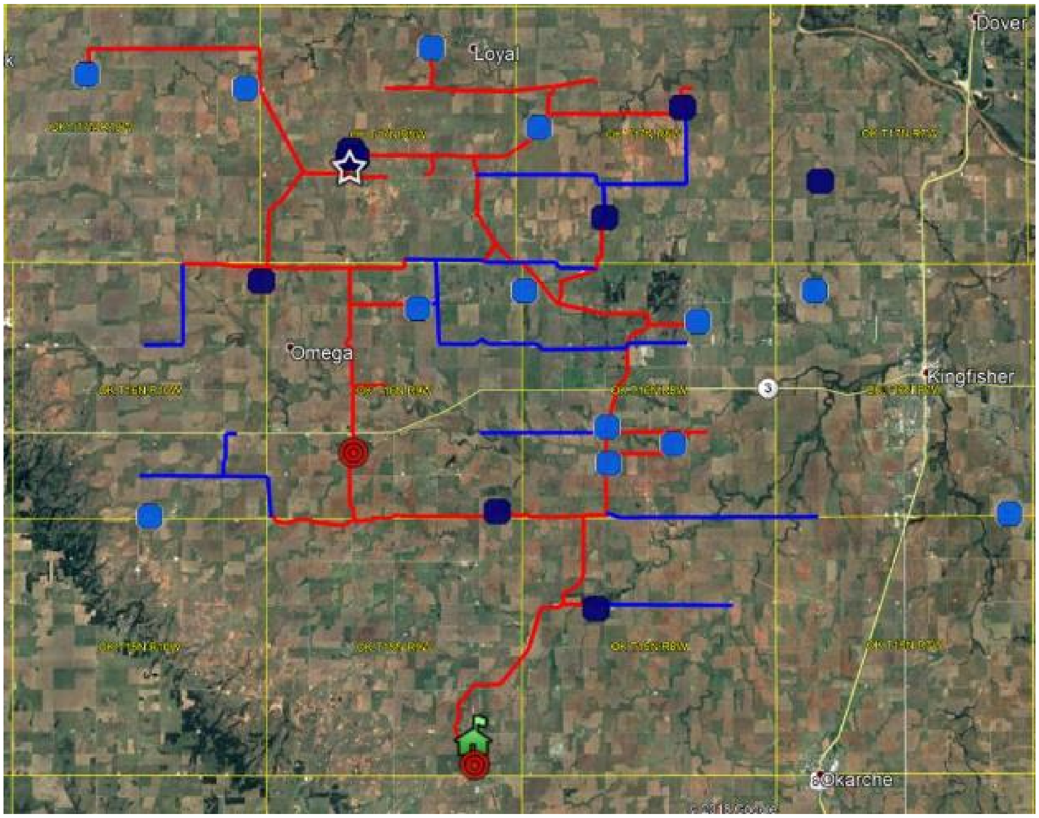

Figure 2-A-6: Newfield STACK Storage, Transportation, Disposal, Treatment and Reuse System

LEGEND

Current operating pipeline system with 75 miles of dual 12" and 6 miles of single 12" SDR7 HDPE pipe

2019 planned additions include 10 miles of dual 12" and 38 miles of triple 12" SDR7 HDPE pipe

10,000,000 bbl. Total storage capacity for fresh water

5,000,000 bbl. Total storage capacity for treated produced water

Barton Treatment and Reuse Facility

Class II SWD UIC wells

Figure 2-A-7: Newfield Barton Produced Water Treatment and Reuse Facility

APPENDIX 2-B: Regional Discussion Summaries and Notes

GWPC Regional Discussion Summary							
Basins/Areas (States covered)	**Bakken** (ND & MT)	**DJ/Niobrara** (CO & WY)	**Eagle Ford** (TX)	**Haynesville** (LA & TX)	**Marcellus/Utica** (PA, WV & OH)	**Oklahoma** (OK)	**Permian** (TX & NM)
Sourcing							
Criteria		Logistics, water rights, water quality	Logistics	Permitting, spills	Cost, Logistics, Regulations, Landowners, Water quality, environmental	Cost, volume available, water quality, logistics, permitting of water and land owner issues	Costs & Logistics
Brackish & Reuse objectives?	Yes	Yes	High priority	Yes	Yes, a priority	Yes	Companies target brackish water.
Challenges	Permitting, Logistics	Water rights, Landowners, Logistics	Landowners, Cost, GCDs (regulatory)	Landowners, permits	Regulatory, including stream pass-by	Drought, availability, competitors, right-of-way, logistics, storage availability, permitting difficulty	Costs, Logistics, scarcity & right-of-way
Reuse							
Challenges	High TDS requires more dilution & has greater spill risk	Costs, regulatory, Landowners, Logistics	Limited PW volumes, Low cost sourcing/disposal	Drilling is scattered, Cost	Pad space for blending, water quality, limited PW volumes, regulations	Cost, spills, logistics, right-of-way, water quality, storage, produced water ownership, accounting	Spills, water quality, well performance
How encourage reuse?	Allow impoundment flexibility, speed approval timing	Regulatory clarity	Limited PW volumes	Impoundment rules in TX considered strict	More regulatory flexibility with storage, reporting requirements	Operator ease to get commercial designation, Incentives	Faster permit approvals, clarity about PW ownership.

GWPC Regional Discussion Summary							
Basins/Areas (States covered)	**Bakken** (ND & MT)	**DJ/Niobrara** (CO & WY)	**Eagle Ford** (TX)	**Haynesville** (LA & TX)	**Marcellus/Utica** (PA, WV & OH)	**Oklahoma** (OK)	**Permian** (TX & NM)
Risks to reuse	Spills	Use outside of oilfield, Spills	PW ownership, Spills, Reservoir impact	bacteria in PW can sour formation, water quality, spills	Spills, sour gas in impoundments, NORM, frac tank costs	Spills, potential impact to production, scale/water compatibility, solids in impoundments	Spills, water quality, well performance, handling solids
Mobile vs permanent treatment	Mobile	Usually mobile	Mobile treatment only	No reuse ongoing	Both	Both	Only mobile treatment
Right-of-way significance	Significant challenge	Significant	Not a huge issue	Significant	Substantial: including stream crossings	Substantial: small land tracts; County ROW issue	Significant
Water treatment efficacy		Not important	Not a huge issue		Occasionally important, especially NORM removal	Occasional problems	Not important
Water storage	Frac tanks most common	Wyoming uses impoundments; Colorado uses tanks.	Impoundments most common	Impoundments most common	Frac tanks and ASTs most common	Impoundments most common	All options used
Discharge outside oilfield?	Minimal	One operator is discharging.	Not asked	One company is evaluating discharge	Yes, Antero and several commercial discharge facilities	No	Anadarko cotton crop only known example
Disposal via SWD							
Disposal concerns?	Overpressuring is a concern	Wyoming operator concerned; CO operator notes SWD limits	Not significant	Overpressuring is a concern	Not too concerned	Not too concerned in SCOOP & STACK	Third party SWDs, overpressuring formation, seismicity
Costs							
Costs only driver?	Stakeholder impact of	No, but it is important	Trucking impact is driver		Environmental and safety are drivers	No, but it is important	No, but it is important

GWPC Regional Discussion Summary							
Basins/Areas (States covered)	**Bakken** (ND & MT)	**DJ/Niobrara** (CO & WY)	**Eagle Ford** (TX)	**Haynesville** (LA & TX)	**Marcellus/Utica** (PA, WV & OH)	**Oklahoma** (OK)	**Permian** (TX & NM)
	trucking is driver.						
Sharing source or PW among operators?	Common disposal lines operated by commercial SWD.	Limited interest in sharing PW.	Occasional sharing of source water	Occasional sharing of source water	Significant sharing between companies	Limited, not common	Limited, not common
How contain costs?				To reduce water costs, companies are: working with the river authorities on multi-year take-or-pay contracts, trying to limit transport distances, & using third party SWDs.			
Miscellaneous							
Legal concerns about PW ownership?	Few concerns	Water ownership is uncertain; Spill liability is PW transferred	PW ownership is concern; liability of spills after transfer	Few concerns	Few concerns	Water ownership is uncertain; Spill liability is PW transferred	Water ownership is uncertain

Permian Regional Call Summary

GWPC organized a group discussion with a group of seven Permian producers. Here are some of the consensus thoughts on water management and produced water reuse:

Sourcing of Hydraulic Fracturing Water

- Two key criteria for water sourcing are cost and logistics.
- Companies are targeting brackish water instead of fresh water, while recognizing that the definition of brackish is not universal. Generally, the oil and gas industry consider 1,000 ppm TDS as a cutoff between fresh and brackish. All companies interviewed are using some level of brackish sourced water with ranges from 15% to 95% brackish use.
- Cost of water and logistics to getting water to the well site are big challenges. Water scarcity is area dependent. Right-of-way can be a problem with landowners and varying county regulations. Some landowners' agreements may require water purchase and thus limit reuse.

Produced Water Reuse

- Challenges to produced water reuse are varied. Avoiding spills is a priority. Water quality for reuse can be a limitation, with some produced water having high total dissolved solids and scale saturation or compatibility issues, that may translate to higher costs. It is important to have high confidence that produced water reuse works as effectively as fresh or brackish on the producing well performance.
- Regulatory factors mentioned related to reuse include getting faster approval of water related permits, especially in BLM areas within New Mexico. Also, clarity on who owns produced water (especially if it is transferred from one producer to another) is still needed.
- Water compatibility and formation of scale are also considerations with reuse. Solids handling, and disposal of solids can be a risk with reuse. The solids may be a result of the treatment process or may build up in the water storage impoundments.
- Operators reported reusing from 0 to 30% produced water for sourced water. Two operators plan to nearly double their reuse by year end. The ongoing water treatment is all performed by mobile water treatment vendors. No permanent plants were being used for treatment.
- Delaware Basin operators estimated that the lifetime of produced water volume could be 4 to 6 times the volume of water used to hydraulically fracture wells. No estimates were given for the Midland Basin.
- A couple of operators reported that no sourced water was being trucked. For disposal, two operators estimated about 5% of produced water was trucked to SWDs or a reuse facility. Trucking was required only when minimum volumes were not sufficient to justify a temporary or permanent pipeline.
- Right-of-way challenges make building a pipeline network difficult. Often, numerous negotiations and payments are required to be able to install water pipelines across surface owners' land.

- Hydraulic fracture chemistry is not too dependent on water treatment, but controlling bacteria is always a top priority. Sometimes total suspended solids and iron may impact the friction reducer. If water is stored in an impoundment, treatment may be important to prevent settling of solids.
- Water storage is often handled with impoundments and above-ground storage tanks by operators at one time or another. The lengths of the drilling plans are important to determining if the higher capital cost of an impoundment can be justified. The decision is based on costs and length of the payout.
- The only known example of reuse outside of oil operations was the Anadarko limited volume test of treated produced water on cotton crops in the Permian.[219]
- A discussion on typical water quality arose. One company cited 50,000 – 70,000 TDS in Reeves county. Another estimated their water TDS in the Delaware Basin to be between 150,000 and 240,000. A third company estimated Wolfcamp produced water to be 35,000 to 50,000 TDS. A fourth company considered Midland Basin water quality to be around 110,000 to 115,000 TDS. As with many other areas in the United States, water quality in the Permian Basin can vary greatly from formation to formation and across geographic distances.

Disposal via SWDs

- Operators thought that there were a variety of concerns related to water disposal:
    - Deeper formations and shallower formations have different characteristics and concerns. For example, in deeper disposal reservoirs injectivity is more unpredictable.
    - Commercial, or third party, salt water disposal (SWD) can be a concern due to the producer not having control of the well integrity, but potentially sharing liability in the event of a spill.
    - Obtaining permits for SWDs may be difficult. Protesting of permits has occurred in some cases.
    - Over pressuring the shallow legacy disposal formation was a risk in the Midland Basin. It can create water flows when drilling through the disposal zone.
    - Seismicity is a potential concern.
    - More deep injection is occurring in New Mexico recently.

[219] OWRB, Oklahoma Water for 2060 Produced Water Reuse and Recycling, April, 2017, 266 pp., https://www.owrb.ok.gov/2060/PWWG/pwwgfinalreport.pdf

Costs

- The consensus is that costs are not the only factor in water management, but it is an important one.

Miscellaneous

- Some sharing of sourced water or produced water among operators was reported but seems limited and uncommon.
- Texas operators do not consider produced water ownership a legal certainty. More could be done to clarify this issue, especially if produced water has value.
- A research idea is to consider the uses of the solids that are created by treating produced water.

Marcellus/Utica Regional Call Summary

GWPC organized a group discussion with a group of six Marcellus/Utica producers. Here are some of the consensus thoughts on water management and produced water reuse:

Sourcing of Hydraulic Fracturing Water

- The criteria for selecting water sources include: cost, proximity and logistics, regulations about surface pass-by flow for stream sourcing, landowner/stakeholder considerations, terrain and elevation changes, water quality when mixing various sources (especially with barium and strontium), and reducing environmental footprint.
- Brackish water and reuse are objectives of water management with the intent to reduce fresh water sourcing and water disposal, however, sometimes water quality is a challenge. One operator is trucking most of its produced water for reuse and blending with other water at the well site. Sometimes there is limited space on the pad for blending. Another company stated that they had 100% reuse in Pennsylvania, but no reuse in Ohio or WV. The lower volumes in Ohio and WV and cost differences make reuse difficult there. A third company is reusing 100% in Pennsylvania. They remove barium and radium in the water treatment and dispose of the solids appropriately. A fourth company has mostly used surface water in Ohio due to its availability and that their small scale operations do not allow a complex system, including reuse. Reuse is a high priority objective for a fifth company. 100% reuse in PA and WV, 10% reuse in OH. They also truck water from OH to PA and WV to be reused. The goal is to have 100% reuse during active fracturing operations. Having adequate produced water storage is important in reducing the costs of reuse. The regulatory challenge of permitting storage sites can be difficult to manage. This company also accepts water from other operators where it is logistically feasible.
- Sourcing challenges include restrictions on pass-by flow conditions in streams and creeks. These restrictions are a significant limitation during the summer. There are also substantial regulatory processes and procedures to follow in order to use a water source. PA regulatory review timelines are a big challenge. It takes a long time to add a water source to the water management plan and then also a long time to develop the infrastructure from the source to the delivery point.

Produced Water Reuse

- The main challenges to reuse noted by the operators are: having sufficient pad space for blending and storage of produced water, water quality considerations caused by the higher salinity produced water, having enough produced water volume to be meaningful, and regulatory issues. Another company said that the inconsistency in their completion operations makes reuse challenging. Other challenges to reuse are regulations on transferring produced water via pipeline and permit requirements for produced water storage sites.
- Regulators could help make reuse easier by allowing more flexibility in various types of storage and reducing reporting requirements to track produced water when it is moved from site to site. The purpose of tracking the actual barrels is not necessarily clear. The actual barrels cannot be definitively tracked when they are often mixed together in storage. Transferring produced water via pipeline is safer with less risk of spills than trucking, yet the regulations often make it difficult to transfer water via pipeline.
- The risks to produced water reuse mentioned by this group were: spills, development of hydrogen sulfide (H_2S) in impoundments (especially in the warmer months), naturally occurring radioactive material (NORM) sludge that may settle out in storage, frac tank storage costs, Health Safety and Environmental (HSE) training, human errors, and slippage of top soil that impacts pipeline integrity. It should be noted that spills are a risk whether trucking water to disposal or trucking to treatment sites for reuse.
- Operators are using a combination of mobile and fixed treatment plants. Producers also take water to a commercial water treatment plants that take and distribute water for multiple operators.
- Operators' estimates of produced water in the life of a Marcellus well as a percent of the frac water ranged from: 10-30%, 10%, 10-15% and 50-70% in the northeast. One suggested that the Utica produced water may be greater than a typical Marcellus well. Two operators said that water operations were in a crisis two years ago when drilling and completion slowed and there was not a reuse outlet.
- Three operators said that 0% of produced water was conveyed via pipe and a third estimated the conveyance by pipe at less than 2%. Thus, the vast majority of produced water is conveyed by truck.
- Right-of-way challenges are significant for permanent and temporary pipelines, even when they are used to transport fresh water. Stream crossings were also mentioned as a significant regulatory hurdle, while the terrain is generally a challenge in the northeast.
- One operator thought of water treatment as a cost, but that transportation for reuse or to disposal was a bigger driver. A second company felt that treatment was very important, especially barium and strontium removal and the associated NORM. Two other producers did not consider water treatment efficacy particularly important.
- Water storage is handled by frac tanks, above ground storage tanks (ASTs) and impoundments. Permitting has been difficult for impoundments and regulators were said to be phasing them out.

Two risks mentioned with any impoundment is overflow due to rainfall and liner failure. Leak detection for liners is now commonly installed.

- One company thought that reuse was 5 to 12% of their sourced water in WV. A second producer estimated that reuse was 20% of their source water in the region. A third producer with very limited completion activity is not currently reusing produced water, but they have reused PW in the past. A fourth company is getting 15 to 20% of their sourced water from reused produced water. Since produced water volumes are much lower than necessary sourced water in this area, the reuse is a much higher percentage of the available produced water.
- Companies mentioned that have discharge permits for a highly treated distillate recovered from produced water are Eureka Resources, Antero/Veolia and Fairmont Brine. Other commercial water treatment facilities may treat produced water for reuse and may not have discharge permits. This includes Hydro Recovery's three plants in Pennsylvania and Fluid Recovery Systems FRS three plants in Pennsylvania.
- One operator found that the Marcellus in northeast PA averaged about 175,000 mg/l of total dissolved solids (TDS), with a range from 100,000 to 200,000 mg/l. In Southwest PA and WV, the range was 150,000 to 250,000 mg/l with an average of 202,000 mg/l. A second producer mentioned that their range was 120,000 to 140,000 mg/l TDS.

Disposal via SWDs

- Most companies are reusing a significant percentage of their produced water and are not too concerned about seismicity, but they continue to follow the topic.

Miscellaneous

- Safety and environmental concerns are as big of a driver as cost.
- Companies did not have concerns about legal aspects of sharing water or were not aware of any issues.
- Companies mentioned having agreements with other producers that allow sharing of produced and fresh water. They also noted that interbasin water transfer of produced or fresh water could be beneficial, but the regulatory hurdle for this is high.
- One company mentioned that the regulatory environment in Ohio was reasonable, but waste transfer across state lines complicates issues between states. Sometimes the regulatory changes in one state in the region can create change in another state.

Eagle Ford Regional Call Summary

GWPC met with a group of seven Eagle Ford producers. Here are some of the consensus thoughts on water management and produced water reuse:

Eagle Ford current water management practices are influenced by the relatively small amounts of produced water in a well's life compared to the volume of water used during the completion. In the life of a typical Eagle Ford, the well may only produce 20 to 30% of the water used in the completion (fracture treatment). The smaller volumes of produced water are more costly to aggregate and distribute for reuse on a per barrel basis than regions with larger water volumes. Additionally, the lower volumes of produced water have not driven up water disposal costs, making produced water reuse economically challenging. Some companies are reusing limited volumes of produced water, but it is usually a special situation warranting the reuse.

Sourcing of Hydraulic Fracturing Water

- Local availability is the primary driver for water sourcing. Most companies use groundwater that varies from fresh water with less than 1,000 mg/L of TDS to brackish or saline water that could exceed 10,000 mg/L TDS. Although operators will try to use brackish water preferentially, sometimes landowners prefer or dictate that fresh water wells be drilled and used as sourced water. The majority of the mineral leases / surface use agreements are written so the producing company drills the sourced-water well for their hydraulic fracturing needs and then cedes the well to the landowner once it is no longer needed.
- Using brackish or produced water is preferred since it reduces demand for fresh water. This is a higher priority in times of drought as in 2011 and 2012. Little surface water is available in the region. STEER (South Texas Energy & Economic Roundtable) commissioned a groundwater study funded by 13 companies to help assess groundwater volumes (fresh and brackish).
- There are a number of challenges in this region for sourcing water. Most companies sourced water for operations from groundwater, however a few companies may also use surface water on occasions.
    - Landowners often stipulate the use of freshwater that provides revenue for them. If produced water is used, in some cases the landowners require payment for the water that normally does not have commercial value.
    - Cost is a significant consideration. South Texas has low costs for sourcing water and disposal of produced water, making reuse economically challenging.

Produced Water Reuse

- One operator said that "Regulations are not stopping reuse in Eagle Ford". The group concurred. Clarity on produced water ownership could help reduce uncertainty. There are still concerns about who owns produced water if it changes leases or is transferred to another producing company. The biggest challenge to reuse is the limited volume of water spread out over a large area. The regulators can't fix the economic challenges with the logistics of water in the area.
- The risks to produced water reuse sited by the Eagle Ford group are:
    - Uncertainty about produced water ownership
    - Spills of produced water due to more transportation and storage
    - The need for more piping to move the water to where it is needed
    - Operating cost impact due to water treatment and other cost factors

    - Potential negative impact on producing reservoir.
- Most of the reuse in Eagle Ford has been with mobile systems as part of short term pilots. One company is known to be reusing produced water now and another has reused previously. One company uses the produced water from new wells for reuse before the salinity increases too much. One "permanent" water treatment plant is located in Eagle Ford. Where water is reused, disposal limitations or trucking costs are often the driver. Generally, disposal capacity and truck options are somewhat limited.
- Most produced water is trucked from a tank battery, collection point, to the SWDs. At least two companies have piping directly to SWDs, but they are the exception.
- Right-of-way needed for water pipelines can be attained at a cost from landowners. It is not a big problem.
- Water treatment efficacy is not a large issue. Since Eagle Ford produced water quality is usually 40,000 mg/L TDS or less and brackish or fresh water would normally be blended to augment the supply, water treatment needs are minimal. The biggest issue with water quality for reuse is bacteria.
- Water storage is most often done in in-ground impoundments. A single liner is sufficient for fresh and brackish water, but a dual lined impoundment may be used if produced water is stored and reused.

<u>Disposal via SWDs</u>

- Seismicity is not a significant concern in south Texas due to the relatively limited volumes of water that must be disposed and limited history of seismic events. Most SWDs are third party operations, although at least one producer owns one or more disposal wells.

<u>Costs</u>

- Besides costs, trucking is a significant issue in water management. Trucking may impact the community with extra traffic and recently truck availability is a concern due to competition from Permian. Secondly, using less fresh water is an objective of some operators.
- Typical trucking costs can average $1 - $1.5 per barrel of water (BW) depending on the distance to the SWD. Water sourcing may cost $0.25/BW plus operating costs and capital costs for the source well that is often provided for the landowner. Third party disposal costs, not including transportation, average $0.35 – 0.60/BW.
- Occasionally, operators will share fresh or brackish sourced water, but produced water has not been shared for reuse in Eagle Ford.

Miscellaneous

- The key challenge to reuse in is the limited amount of produced water spread out over a large area. The limited volume increases gathering costs per barrel. Additionally, the relatively low cost of sourcing and disposal makes the economic proposition very difficult.
- Regulators or legislators could help with rule changes that would provide legal or regulatory certainty when custody of water is transferred. Currently, there is not clarity that the responsibility for the produced water transfers with the custody. A clear handoff of liability is needed if operators are going to share produced water for reuse. Water ownership is also an area that needs more clarity and certainty to facilitate produced water sharing.

Central Oklahoma Regional Call Summary

GWPC met with a group of about a dozen Oklahoma producers. Here are some of the consensus thoughts on water management and produced water reuse:

Sourcing of Hydraulic Fracturing Water

- The criteria to select sourced water for hydraulic fracturing are: cost, volume available, chemical compatibility (water quality), logistics of water, permitting of water and land owner issues.
- Reusing or sourcing brackish is preferred to fresh water if the costs are similar or better. Other factors include spill risks or other health, environmental, and safety issues.
- Sourcing challenges are: drought, availability, competitors, right-of-way agreements with landowners and county governments, proximity of source to location, storage availability, permitting difficulty (it was noted that the 90-day temporary permit is being somewhat restricted now).

Produced Water Reuse

- The challenges to reuse are: cost, spills, logistics including county road right-of-way, water quality and completion design, storage of produced water/permitted impoundments, legality of produced water ownership, accounting (paying entities when water transferred).
- Regulators could make selective changes that would encourage reuse.
    - If it were easier for an operator to get a commercial designation, it would make sharing among companies easier and encourage reuse.
    - Tax relief for reuse would incentivize the practice, but the group realizes that this is complicated by a very tight state budget.
- Risks to produced water reuse include: spills, potential impact to formation and production, scale/water compatibility, and solids in impoundments.
- For water treatment, operators are using a mix of fixed water plants and mobile water treatment facilities. Problems from limited or poor water treatment may create problems with solids in impoundments, oil slugs at treatment facilities, or frac chemistry problems due to water quality.

- Within the lifetime of a well, perhaps 30 to 40% of the frac volume returns in the first year or two. Longer term, water production information is limited. There are only a small number of older STACK/SCOOP wells with 5 years history.
- The estimated percentage of produced water conveyed via pipe to a SWD ranged from 0%, 10%, 20% and ~50% from different producers. The volumes of water and the well spacing impacts whether a pipeline for the water can be justified. If produced water is collected by pipeline, it offers an easier opportunity to logistically make water reuse viable.
- Right-of-way is needed to build a pipe network. Oklahoma has more small surface tracts making the right-of-way process more involved than areas with large tracts of land. In some cases, surface owners or counties may limit produced water in temporary lines, which greatly reduces the ability to reuse produced water.
- Typical produced water quality in total dissolved solids (TDS) was mentioned by operators to be 30,000; 15,000-30,000; 40,000-60,000; 15,000-18,000; and 15,000-150,000 (multiple counties) for central Oklahoma.
- Water is typically stored in impoundments, especially where long term drilling is expected. Above-ground storage tanks (ASTs) are used when a company has limited drilling plans in an area.
- No one knows of any reuse of produced water for discharge or reuse outside of the oil and gas operations now or historically in Central OK.

<u>Disposal via SWDs</u>

- Water disposal concerns in the STACK and SCOOP (Central OK) were minor due to the limited water production volumes. The group felt that drought might be a bigger concern for sourcing than overpressuring or seismicity is for disposal.

<u>Costs</u>

- Costs are a driver for water management, but other factors are important too. Water availability and other risks can be important aspects.
- OCC changed a rule two years ago making sharing among operators easier. Sharing of water has occurred occasionally, but is not common.

<u>Miscellaneous</u>

- Two legal issues were mentioned as important. The first issue is the ownership of produced water when shared among operators. The second legal concern is the potential liability if produced water is transferred to another company and the water is spilled. Legal clarity is paramount to companies working together.
- Oklahoma leasehold and surface ownership is much more fractionated than Texas. Having many relatively small tract owners makes reuse more difficult.

- The opportunity for water midstream may be more limited in central Oklahoma than in the Permian Basin due to less water produced and lower need for infrastructure.
- Groundwater, especially brackish, is limited in volume, produces at low rates and often has TDS levels higher than the produced water.
- State regulation is better than federal regulation because it can be tailored to the regional/local conditions. EPA/federal regulations represent a higher risk of impeding operations.

Niobrara/DJ Regional Call Summary

GWPC met with a group of five Niobrara/DJ producers. Here are some of the consensus thoughts on water management and produced water reuse:

Sourcing of Hydraulic Fracturing Water

- Operations for the group cover Wyoming and Colorado. Important aspects of sourcing water include proximity to the location where it is needed (logistics), having existing water rights, and the water quality.
- In some cases, companies may prioritize reuse of PW over brackish, but brackish is prioritized over using fresh water. The costs/economics are important.
- The challenges to sourcing water in this region are varied. Having sufficient water for sourcing, confirming water rights and not competing with farmers is important to one operator. Another poducer indicates that pre-existing land agreements often limit options and that the large land tracts give landowners significant sway. A third operator points to logistical and infrastructure costs as challenges for sourcing water.

Produced Water Reuse

- The challenges to reuse in the Niobrara/DJ are also varied. The cost to treat, store and transport PW is an impediment for reuse. The regulatory framework, especially to discharge in CO, is complex. Another operator suggested that land agreements and unclear regulation is a challenge to reuse. A third operator noted that treatment costs have decreased, but water conveyance infrastructure is needed.
- Regulation of produced water reuse could be improved. Clarificaton of rules was identified as a potential way to encourage reuse.
- The risks to produced water reuse differed among the group. If an operator adds produced water to a system that was previously fresh, the entire system is classified as waste water and limits options. Another company suggested that water chemistry issues have mostly been solved, but trucking and use outside of the oil operations have risks. A third operator noted the risks of spills with reuse.
- The type of treatment systems used depends on the long-term plans. One operator has used skid mounted mobile water treatment, but it usually stays in one location semi-permanently. Other operators are generally using mobile units, but one is considering a fixed treatment plant.

- Produced water is conveyed via pipe and truck in the region.

Operator	Sourcing	Disposal
A	all piped	mostly piped
B	99% piped	1% piped
C	All piped	40% piped

- Right-of-way and landowner challenges to building out a pipe network in the basin are significant challenges. Reuse is difficult without a pipe network to convey water.
- Water treatment effectiveness is not a critical issue for reuse. Other factors are more important.
- Water storage is handled differently by state. Wyoming operations are using impoundments and Colorado operations are using tanks.
- None of the five operators have discharged produced water or reused outside of their operations, but they were aware of one CO operator that is/was discharging treated PW.

Disposal via SWDs

- One Wyoming operator expects disposal limitations in the future. CO operators note less concern than in the past, but SWD pressure and rate limits apply.

Costs

- Cost may not be the only issue, but it may be the most important one right now.
- Source costs may range from 25 to 50 cents/BW. Disposal costs vary from 50 cents to $4/BW. Trucking averages $1.50 to $2.00/BW typically.
- Midstream water companies could offer shared options that reduce cost. A couple of operators are interested in potential midstream solutions, but others are concerned about regulatory issues and liabilities.

Miscellaneous

- Legal concern about water reuse range from ownership of the produced water to liability if water is transferred to another operator. One company noted that they are sharing water in the Delaware Basin (west Texas – Permian Basin), but not in the DJ.
- The companies estimate 30 to 40% of the frac water volume is produced back in the life of the well. This is important as it relates to the potential for reuse to reduce fresh or brackish sourced water and the potential to reduce disposal through reuse.

Bakken Regional Call Summary

GWPC conducted a call with about a half dozen leading Bakken producers. Here are some of the consensus thoughts on water management and produced water reuse:

Sourcing of hydraulic fracturing water

- Brackish and non-fresh water sources are used situationally when it is practical. Companies prefer to use non-fresh because it is best to leave the fresh water for the other stakeholders.
- Sourcing challenges arise when fresh water is not available. Other challenges include water sourcing permits changing, the rare drought, logistics (moving water where it is needed) and having a backup plan for contingencies.

Produced Water Reuse

- Bakken produced water quality typically ranges from 200,000 mg/l total dissolved solids (TDS) to 320,000 mg/l TDS. The high TDS produced water will require more fresh water to dilute it for reuse than many of the other plays. The high TDS also carries higher risks if spilled.
- Several operators reported that they are not currently reusing produced water in the Bakken, even if they reuse water in other regions. Two operators reported reusing less than 5% of their produced water, often for workovers.
- The challenges to reuse are varied. Because there is abundant fresh water and disposal, the economic proposition is difficult for reuse. State regulations limit large impoundments for storage of produced water, increasing the storage cost for reuse. Logistical costs of moving produced water to a site for reuse are also an impediment. Blending requirements for the high TDS Bakken water also increase the complexity and cost of reuse.
- Regulators could potentially encourage reuse by allowing large impoundments for storage and blending of produced water. Regulators could also try to improve approval timing so that reuse would become reliable and predictable.
- Spills are the primary risk with reuse. Spill risk can be present when conveying or storing produced water. Blending logistics and operations with reuse introduce operations risks. One of the operators that have reused water noted that naturally occurring radioactive material (NORM) has not been a significant problem.
- Water treatment is not needed for most of the ongoing water reuse. Previously, one company used reverse osmosis treatment, but that operation has been discontinued.
- Most companies report that the produced water volume represents a range of 40 to 100% of the volume used in the completion. Individual wells have varying volumes.
- Companies estimate that 30 to 85% of the produced water is conveyed via water pipelines to disposal wells with the remaining balance being transported by trucked. Piped water generally has a lower spill risk and reduces the road traffic. The percentage of piped produced water is expected to continue growing.

- Obtaining right-of-way for water pipelines (sourcing or produced) is a significant challenge. Legislation facilitates oil and gas line right-of-way, but water does not have the same rights.
- Frac tanks are by far the most common method of storing fresh or produced water for use in completions. Impoundments are generally not used due to regulatory constraints. Above-ground Storage Tanks (ASTs) are used infrequently. Cold weather and required heating tend to encourage operators to store minimal water. In some cases, companies avoid completions in the winter because of freezing issues.
- The group of operators were only aware of minimal reuse outside of oil and gas operations. In a very limited number of cases the use of produced water for dust control has been permitted. The North Dakota Department of Health has specific parameters that must be met.[220]

Disposal via SWDs

- Disposal capacity concerns about the Dakota formation have arisen recently. Over-pressuring has occurred in limited areas where industry activity may be particularly high. North Dakota regulators and industry are engaged to coordinate activity to reduce over-pressuring of the disposal formation. Seismicity in the Bakken region has not been a concern. The area is one of the least active areas for seismicity where companies operate.

Costs

- The top area identified to reduce water costs and stakeholder impacts is the installation of sourcing and produced water pipelines. Most companies noted ongoing plans and projects to install water pipelines and reduce trucking of water.
- The Bakken is unique in that it has the coldest winters of any US unconventional region. Correspondingly, the cost of heating water to prevent freezing is more significant than in other basins.
- There are several third parties that gather produced water in pipelines and dispose of it in disposal wells. Goodnight Midstream is one of the larger Bakken water gathering companies. Companies did not currently report sharing of water directly between companies.

Miscellaneous

- One company noted legal concerns about produced water ownership when there would be a change in custody among companies. Since water sharing is not occurring, this has not been a significant issue.

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[220] North Dakota Administrative Code, Guidelines for the Use of Oilfield Salt Brines for Dust and Ice Control, NDAC §33-24-02-02(5)(a)(2), 4 pp., https://deq.nd.gov/Publications/WQ/1_GW/general/IceDustControlUsingOilfieldBrine_20130321.pdf

Haynesville Regional Call Summary

GWPC conducted a call with several leading Haynesville producers. Here are some of the consensus thoughts on water management and produced water reuse:

Sourcing of Hydraulic Fracturing Water

- Using brackish water and reusing produced water are objectives for sourcing, but other factors need to be considered such as permitting constraints, risk of spills, groundwater availability, and other water source options.
- Sourcing challenges include: landowner agreements that may complicate water options, the US Corps of Engineers have constraints and permits for sourcing water from federal property, and Texas state rules are more difficult than Louisiana rules.

Produced Water Reuse

- A typical range of total dissolved solids in Haynesville produced water is 75,000 to 175,000 mg/L.
- The companies interviewed are not currently reusing produced water but are aware of an operator reusing water. One producer is considering discharge of treated produced water.
- The primary challenge to reuse in the Haynesville is that it is not cost effective compared to other options. For example, the storage impoundments for produced water are much costlier than impoundments for fresh water. Also, much of the drilling is still in the early delineation phase where wells are scattered around. In this phase, it is more difficult to develop an effective reuse system.
- Companies noted several items that regulators could improve: the impoundment rules for Texas are considered restrictive; the Texas Railroad Commission has challenging limits for chlorides in groundwater when a cleanup is needed; one company is considering treated produced water discharge in the region, but the process is complex.
- There are several risks with produced water reuse: introducing bacteria from produced water can introduce hydrogen sulfide (H_2S) to a formation where it was not previously known to exist; using produced water for fracturing can risk chemical compatibility issues; surface spills of produced water may increase with reuse; and in some cases, reuse may require water treatment.
- Water treatment efficacy can be important in some cases. More complex water treatment systems cost more than simple treatment systems.
- The amount of water produced over the lifetime of a typical well ranges from 10 to 50% of the volume of water used in the completion. The water production drops off rapidly over the first year of production.
- Companies currently have very limit produced water conveyed to disposal by pipe. Estimates range from 0 to 2% transported by pipeline. The other 98% of produced water is trucked to SWDs.
- Right-of-way challenges are significant if water is transferred from a lease by pipeline. The cost of getting right-of-way becomes an impediment.

- Water storage before the completion operation is often in unlined impoundments when using fresh water.
- There is no known produced water discharge in the region, but one company is evaluating discharge due to current disposal reservoirs becoming charged with pressure from historical disposal.

<u>Disposal via SWDs</u>

- Some companies are concerned about increasing pressures in disposal formations. The problem initially occurred in northeast Texas, but now has the attention of Louisiana regulators. Seismicity in the area has been quiet since a couple of small earthquakes in Timpson, TX a few years ago.

<u>Costs</u>

- To try to contain or reduce water costs, companies are: working with the river authorities on multi-year take-or-pay contracts, trying to limit transport distances of produced water, and using third party disposal wells.
- Typical costs for fresh water may range from 5 to 30 cents per barrel. Trucking costs may range from $0.75 to $1.50 per barrel. Third party disposal costs average about $1 per barrel.
- Occasionally, operators will share a water source with another producer. There is one small commercial reuse facility in northern Louisiana.

<u>Miscellaneous</u>

- Produced water ownership concerns have not been significant due to limited sharing among operators. There is some hope that extraction of minerals such as lithium from produced water or sludges from treated produced water could be viable one day and the ownership of produced water could become more critical.

APPENDIX 3-A: EPA Centralized Waste Treatment Study – Executive Summary (2018)*

1. EXECUTIVE SUMMARY

The U.S. Environmental Protection Agency (EPA) regulates discharges from centralized waste treatment (CWT) facilities through the existing effluent limitations guidelines and pretreatment standards (ELGs) found at 40 CFR Part 437. CWT facilities accept for treatment, recovery or reuse a variety of wastes and wastewaters. EPA first promulgated the CWT ELGs in 2000. At that time, while EPA was aware that some CWT facilities were accepting wastes from oil and gas extraction activities, this practice was not prevalent.

Since 2000, CWT facilities have been increasingly used to manage wastes such as produced water, drilling wastes and hydraulic fracturing fluids generated by oil and gas extraction operations. This is due to a number of factors, such as the increased utilization of hydraulic fracturing to extract oil and gas. Given changes in the industry since 2000, particularly with respect to management of oil and gas extraction wastes, EPA has undertaken a detailed study of the CWT industry. A primary goal of the study is to determine if the existing CWT regulations should be updated given changes in the industry, specifically related to facilities that accept oil and gas extraction wastes.

As part of this study, EPA has evaluated several aspects of the CWT industry. This report details several areas, including:

- The current universe of 40 CFR Part 437 CWT facilities that EPA is aware of that accept oil and gas extraction wastes for discharge either directly to waters of the United States or indirectly via publicly-owned treatment works (POTWs). A lesser focus are facilities that accept oil and gas extraction wastes and discharge under a different effluent guideline (such as the Oil and Gas Extraction ELGs at 40 CFR Part 435) and facilities that accept oil and gas extraction wastes but do not discharge (i.e., facilities that treat for recycle or reuse).
- The current regulatory status of these facilities, including the basis for National Pollutant Discharge Elimination System (NPDES) permits issued to these facilities, factors such as the wastewater parameters contained in these permits, and the types and quantities of wastes accepted for management.
- Characteristics of wastewaters from oil and gas extraction activities that are currently or could potentially be managed by CWT facilities.
- Technologies applicable to treatment of wastewaters from oil and gas extraction activities, including their cost and performance.

* USEPA, Detailed Study of the Centralized Waste Treatment Point Source Category for Facilities Managing Oil and Gas Extraction Wastes, EPA-821-R-18-004, Executive Summary, pp. 1-1 – 1-4 (May 2018).

- Economic and financial characteristics of the CWT industry and facilities that manage oil and gas extraction wastes.
- Documented and potential human health and environmental impacts of discharges from CWT facilities managing oil and gas extraction wastewater.
- Generation and management of treatment residuals at CWT facilities, and transfer of pollutants to other media (solid waste, air emissions).

EPA has collected data from a variety of sources, including publicly-available information (facility permits, literature), Clean Water Act (CWA) section 308 data collection, and wastewater sampling.

EPA has made the following observations regarding the CWT industry and CWT facilities that manage oil and gas extraction wastes:

- Although EPA has identified many existing CWT facilities, little information is readily available to determine whether some of these facilities would be affected by changes to EPA's existing regulations at Part 437. A primary data gap is knowledge about the types of wastewaters accepted, specifically whether wastewater from oil and gas extraction facilities are accepted, and the basis for NPDES permits issued to these facilities.
- EPA identified 11 facilities that accept oil and gas extraction wastes as of 2017, discharge those wastes after treatment and are subject to the Part 437 ELGs (or information available to EPA indicates will be subject to Part 437 when permits are re-issued). These are the facilities considered to be "in-scope" for the purpose of this study.
- Oil and gas extraction wastes can contain a variety of constituents, including biochemical oxygen demand (BOD), bromide, chloride, chemical oxygen demand (COD), specific conductivity, sulfate, total dissolved solids (TDS), total suspended solids (TSS), barium, potassium, sodium, strontium, benzene, ethylbenzene, toluene, xylenes, sulfide, gross alpha, gross beta, radium 226, and radium 228.
- The pollutants present in and characteristics of oil and gas extraction wastes can vary greatly. Factors that can influence the pollutants contained in and the characteristics of these wastes include the source formation for the oil and gas, the type of drilling and whether stimulation methods are used, the types and quantities of additives used during drilling and well development, and the age of the well.
- The range of pollutants present in these wastes typically require the use of a multi-step treatment train to meet discharge standards.
- Of those facilities that are in-scope for this study, variation exists in types of treatment technologies employed. Some facilities employ multi-step treatment systems specifically designed to remove pollutants commonly found in oil and gas extraction wastes. Other facilities use treatment, such as chemical precipitation, that remove specific pollutants but provide little or no removal of the many other pollutants commonly found in these wastes. As a result, some facilities discharge much greater quantities of pollutants, such as total dissolved solids and chlorides, than others.

- Costs for technologies to remove TDS can be high, but nonetheless can be cost-competitive when factors such as transportation to alternate treatment or disposal methods (such as to injection wells) are considered. In addition, technologies (such as evaporation) are available that use waste heat from other industrial sources that, where co-located, can significantly reduce costs of treatment.
- EPA approved analytical methods do not exist for many constituents found in oil and gas extraction wastes. In addition, some constituents (such as total dissolved solids) found in oil and gas extraction wastes can interfere with EPA approved analytical methods and significantly affect the ability to detect and quantify the level of some analytes.
- The current ELGs at 40 CFR Part 437 do not contain limitations for many of the pollutants commonly found in oil and gas extraction wastes. Many of these pollutants are not included on the current list of priority pollutants.
- The manner in which permitting and control authorities have permitted facilities that accept oil and gas extraction wastes for discharge varies. Some facilities are permitted under Part 437 while others are not. As a result, discharge limitations in permits are not consistent across the industry. A number of facilities operate under expired permits that do not contain limitations for many of the pollutants found in oil and gas extraction wastes; several facilities are in the process of permit renewals that may change the limitations contained in future permits.
- A lack of clarity exists among the regulated community regarding applicability of the current CWT effluent guidelines to facilities that treat oil and gas extraction wastes. Some of this is centered on the interpretation of what constitutes “off-site” in the context of oil and gas operations and whether Part 437 or Part 435 effluent limitations should be applied to facilities treating oil and gas extraction wastes. While EPA has provided clarification of this for operations in the Marcellus Shale region, questions still arise.
- The cyclical market for commodities, including the recent drop in oil and gas prices from 2014 through 2016, has affected the CWT industry that accepts oil and gas extraction wastes. Data available to EPA indicates that some facilities have reduced operations or ceased operating, in part because producers have also reduced operations or ceased operating or sought cheaper wastewater management solutions. In addition, several new discharge permits have been issued for facilities that have yet to be constructed, in part because of the reduced demand for treating wastewater for discharge. It is not clear if or when these facilities may be constructed or begin operations.
- The demand for CWT services is directly related to the amount of wastewater requiring management. If increased oil and gas exploration occurs in the future, an increase in the volume of wastes produced would also be expected. It is difficult to predict whether the demand for oil and gas CWT services will increase or decrease in the future, as that demand is directly tied to commodities that are subject to market fluctuations. In addition, competition exists from other management options, such as disposal wells. However, concerns regarding induced seismicity and reduced disposal well capacity may result in greater demand for CWT facilities treating these wastes.
- Removal of barium and co-precipitation of radium may create a solid waste management issue at CWT facilities treating oil and gas extraction wastes. More efficient barium removal from the

wastewater in the presence of sufficient radium may result in solid waste that exhibits radioactivity at levels that preclude disposal in most landfills. In addition, it is plausible that radioisotopes in wastewater treatment residuals disposed in landfills may subsequently be released to the environment through leachate. The level of radioactivity present in oil and gas extraction wastes is a function of source formation characteristics.

- Management of brines and salts produced from technologies such as reverse osmosis, evaporators, and crystallizers may present a solid waste management issue. Disposal of these residuals in landfills has the potential to increase salinity of landfill leachate. Residuals that have marketable characteristics can be produced at CWT facilities. Producing saleable residuals or materials that can be beneficially reused may offset treatment costs. Other management options for these residuals include injection into disposal wells.
- CWT effluents may have elevated levels of TDS, halides, metals, and technologically enhanced naturally occurring radioactive materials (TENORM) relative to the receiving streams into which they are discharged dependent upon the treatment technology utilized by the CWT. These elevated concentrations are detectable in samples collected downstream of CWT facility discharge points. The distance over which these elevated concentrations are detectable depends on site-specific factors such as source formation, CWT facility discharge volume, upstream concentrations of constituents, and river flow.
- Documented and potential impacts to both aquatic life and human health related to discharges from CWT facilities treating oil and gas extraction wastewater exist due to the prevalence of some pollutants. Levels of pollutants downstream from CWT facility discharges have been reported to exceed applicable thresholds, such as primary and secondary drinking water standards and acute and chronic water quality criteria for protection of aquatic life.
- In a number of cases, CWT effluents have been shown to adversely affect downstream aquatic life and, in one case, have been shown to affect survival of riffleshell mussels, a federally-listed endangered species (e.g., Patnode et al., 2015).
- Multiple drinking water intakes are situated downstream of CWTs accepting oil and gas extraction wastewater within distances at which impacts to drinking water from CWTs have previously been identified. Drinking water treatment plants downstream of CWT facilities treating oil and gas extraction wastewater have noted a shift in the composition of DBPs from mostly chlorinated DBPs to mostly brominated DBPs (McTigue et al., 2014), which are more toxic than their chlorinated analogues. These shifts could affect human health from consumption of treated waters.

APPENDIX 3-B: Wyoming Form C: Application for Permit to Surface Discharge Produced Water

SUBMIT ONE HARD COPY AND ONE ELECTRONIC COPY (CD)

WYOMING POLLUTANT DISCHARGE ELIMINATION SYSTEM
APPLICATION FOR PERMIT TO SURFACE DISCHARGE PRODUCED
WATER FROM OIL AND GAS PRODUCTION UNIT DISCHARGES

January 2019

For Agency Use Only
Application Number
WY00______________
Date Received:
______________ (mo/day/yr)

PLEASE PRINT OR TYPE ***(Submission of illegible materials will results in return of the application to the applicant)***

1. The discharging facility will produce:

Oil ☐ Oil and natural gas ☐ Natural gas ☐

Check the box corresponding to the type of application being applied for:

☐ New Permit

☐ Permit Renewal. Permit number ____________ Expiration Date: ______________

☐ Permit Modification. Permit number ____________ Expiration Date: ______________

(For permit modification, please attach letter explaining modifications requested.)

2. **Company, Contact Name, mailing address, e-mail address, and telephone number** of the individual or company, which owns the facility producing the discharge, and the person (consultant) responsible for, permit submission.

Company Contact Name	*Consultant Contact Name*
Company Name	*Company Name*
Mailing Address	*Mailing Address*
City, State, and Zip Code	*City, State, and Zip Code*
Telephone Number	*Telephone Number*
Valid e-Mail Address (Required)	*Valid e-Mail Address (Required)*

Status of applicant as owner, operator or both ____

Status of applicant as federal, state, private or public ____

3. Name of the facility (lease, tank battery #, etc.) producing the discharge (this is the facility name that will appear on the WYPDES permit. It is not necessary to name every well contributing to this facility's discharge in this section)

____

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4. Name(s) and mailing address(es) of owner(s) of the surface rights on whose land the discharge occurs (in cases where the land is owned by the state or federal government but surface rights are leased to a private individual, provide lessee's name and address):

Landowner #1 Name	*Landowner #2 Name*
Mailing Address	*Mailing Address*
City, State, and Zip Code	*City, State, and Zip Code*
Landowner #3 Name	*Landowner #4 Name*
Mailing Address	*Mailing Address*
City, State, and Zip Code	*City, State, and Zip Code*

5. Provide outfall information in Table 1 below.

TABLE 1. Outfall information

** The mainstem is the closest perennial water (class 2). Stream distance from the outfall to the mainstem should be measured in stream miles versus as "the crow flies".*

Discharge Point (Outfall) #	**Immediate Receiving Stream**	**Mainstem*** **(Nearest Perennial Water)**	**Distance from outfall to main stem (stream miles) ***	**Quarter/ Quarter**	**Section**	**Township**	**Range**	**Latitude** (NAD 83, decimal degree format, accuracy to nearest 5 decimal places)	**Longitude** (NAD 83, decimal degree format, accuracy to nearest 5 decimal places)	**County**
001										
002										
003										
004										
005										
006										
007										
008										

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6. Describe measures to prevent access to the skimming ponds by large grazing animals. ______________________

____

____

7. Describe measures employed to deter/exclude migratory birds from the skimming ponds.

____

____

8. As part of the application, the applicant shall certify under penalty of perjury that the applicant has secured and shall maintain permission for Department of Environmental Quality personnel and their invitees to access the permitted facility, including (i) permission to access the land where the permitted facility is located, (ii) permission to collect resource data as defined by Wyoming Statute § 6-3-414, and (iii) permission to enter and cross all properties necessary to access the permitted facility if the facility cannot be directly accessed from a public road. **A map of access route(s) to the facility shall accompany the application.**

9. Attach a description and clear, legible, detailed topographic map of the discharging facility extending one mile beyond the property boundaries of the source. The following must be included:

a. A legend
b. Discharge points (outfalls)
c. Immediate receiving streams
d. Section, Township, and Range information
e. Well locations
f. Water flow lines
g. Wells, springs, other surface water bodies, drinking water wells, and surface water intake structures listed in public records, or otherwise known to the applicant in the map area.
h. Hazardous waste treatment, storage, or disposal facilities
i. Access routes

10. Attach a site diagram. The following must be included:
a. Water flow lines
b. Treater units
c. Skimming tanks
d. Skimming Ponds
e. Stock tanks

(If any of the above items in 8 or 9 are not applicable please indicate in the description and include a brief explanation as to why the items are not applicable).

11. Describe the control measures that will be implemented to achieve water quality standards and effluent limits. If proposing to utilize a treatment process, provide a description of the treatment process. **Include list of chemicals** used and provide a Material Safety Data Sheet (MSDS) for each chemical. If you are using more chemicals than you can list below please provide the complete list as an attachment.

____

____

____

12. Describe the control measures that will be implemented to prevent significant damage to or erosion of the receiving water channel at the point of discharge.

____

____

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13. For facilities that utilize mechanical treatments systems, other than skim pits and heater treaters, please provide a schematic line drawing showing the water flow and water balance through the facility. The water balance must show approximate average flows at intake and discharge points and between units, including treatment units. If a water balance cannot be determined, a pictorial description of the nature and amount of any sources of water and any collection and treatment measures may be provided.

14. Provide a list of all potential pollutants expected to be in the discharge and an explanation of their presence in the discharge.

____

____

____

____

____

____

15. Provide the results of a water analyses for a sample collected from a location representative of the quality of water being proposed for discharge for the parameters listed below, in Table 2.

The analyses must be conducted in accordance with approved EPA test procedures (40 CFR Part 136). Include a signed copy of your lab report that includes the following:

a. Analytical method
b. Results of each of the chemical parameters at the chemical state given below
c. Quarter/quarter, section, township and range of the sample collection location
d. Time and date of sample collection
e. Time and date of analysis for each parameter
f. Detection limit for each parameter as achieved by the laboratory.

TABLE 2

PARAMETER	REQUIRED DETECTION LIMIT and Required Units	STANDARD OR LIMIT*	SAMPLE RESULTS (Also submit lab results with application)
Aluminum, Dissolved	**50 ug/L**	750 ug/L	
Arsenic, Total	**1 ug/L**	150 ug/L	
Barium, Total (*New Facilities Only*)	**100 µg/L**	2000 ug/L	
Boron, Dissolved (*New Facilities Only*)	**100 ug/L**	5000 ug/L	
Cadmium, Dissolved	**5 ug/L**	0.25 ug/L (hardness dependent)	
Calcium, Dissolved	**50 ug/L, report as mg/L**		
Chloride – Technology Based	**5 mg/L**	2000 mg/L	
Chloride, For Class 2A and 2B Waters	**5 mg/L**	230 mg/L	
Chromium, Total	**1ug/L**	74.1 ug/L (hardness dependent)	
Copper, Dissolved	**10 ug/L**	9 ug/L (hardness dependent)	
Fluoride, Dissolved (*New Facilities Only*)	**100 ug/L**	4,000 ug/L	
Hardness (CaCO3) mg/L	**10 mg/L as $CaCO_3$**	(for metals analyses)	
Iron, Dissolved	**50 ug/L**	1000 ug/L	
Iron, Dissolved, for Class 2A and 2AB	**50 ug/L**	300 ug/L	
Lead, Dissolved	**2 ug/L**	2.5 ug/L (hardness dependent)	
Magnesium, Dissolved	**100 ug/L, report as mg/L**		
Manganese, Dissolved	**50 ug/L**	1462 ug/L (hardness dependent)	
Manganese, Dissolved, for Class 2A and 2AB	**50 ug/L**	50 ug/L	
Mercury, Dissolved	**1 ug/L**	0.77 ug/L	
Molybdenum, Dissolved (*New Facilities Only*)	**100 ug/L**	300 ug/L	
Nickel, Dissolved	**10 ug/L**	52 ug/L (hardness dependent)	
Oil and Grease	**5 mg/L**	10 mg/L	
pH	**0.1 pH unit**	6.5-9.0 s.u.	
Radium 226, Total	**0.2 pCi/L**	5 or 60 pCi/L	
Radium 228, Total **	**0.2 pCi/L**	5 pCi/L	
Selenium, Total	**5 ug/L**	5 ug/L	
Silver, Dissolved	**3 ug/L**	3.4 ug/L (hardness dependent)	
Sodium Adsorption Ratio	**Calculated as unadjusted ratio**		
Sodium, Dissolved	**100 ug/L, report as mg/L**		
Specific Conductance	**5 micromhos/cm**	7500 micromhos/cm	
Sulfates	**10 mg/L**	3000 mg/L	
Sulfide-Hydrogen Sulfide (S2-, HS-)	**0.1 mg/L**	2 ug/L	
Total Dissolved Solids	**10 mg/L**	5000 mg/L	
Total Petroleum Hydrocarbons	**1 mg/L**		
Zinc, Dissolved	**50 ug/L**	118.1 ug/L (hardness dependent)	

**The values listed in the Standard or Limit column are associated with water quality standards (Chapter 1 of Wyoming Water Quality Rules and Regulations) or technology-based effluent limits (Chapter 2 of Wyoming Water Quality Rules and Regulations).*
***This parameter is only required for those discharges located within one stream mile of a class 2 water.*

16. Which geologic formation is the origin of the produced water? ______________________________

17. Were the above analyses collected from this facility (referenced in item 3)?

☐ **YES** ☐ **NO**

If no, describe origin of samples including well name, location, depth, geologic formation, field, and date sample was analyzed:

____

18. **<u>For new facilities,</u>** provide the expected (estimated) flow rate from each outfall in barrels per day and million gallons per day, and provide the rationale behind the flow rate estimate:

____

Expected date of commencement of discharge:

____

<u>For existing facilities,</u> provide actual flow data from each outfall within the last six months

Will discharge be ☐ **continuous** or ☐ **intermittent**?

If the discharge is to be intermittent the following information for each outfall shall be provided:
(I) Number of times per year the discharge is to occur.
(II) Anticipated duration of each discharge.
(III) Anticipated flow of each discharge.
(IV) Months in which discharge is expected to occur.

19. Are any of the required chemical constituents in the laboratory analysis present in concentrations above Wyoming Water Quality Standards or limits as identified in the third column in Table 2, page 5?

☐ **YES** ☐ **NO**

If the answer to question # 19 is yes, answer 19a.–19.c below. If no, proceed to question 20.

a. **Which constituents?** ______________________________

b. **Has this constituent been addressed in the response to question 10?** ______________________________

c. **Describe how the exceedance was addressed:** ______________________________

____

20. Will blending of fresh water with produced water be used as a treatment option?

☐ **YES** ☐ **NO**

If the answer to question # 20 is yes, answer 20a.–20.c below. If no, proceed to question 21.

a. What is the anticipated blending rate of fresh water and produced water? ______________________________
Be advised that permit will require water quantity and quality monitoring before and after blending occurs. In addition, an automated shutdown system must be installed and maintained on site that terminates the discharge of produced water in the event of the shutdown of the fresh water supply.

b. Provide confirmation from the State Engineer's office of fresh water use.

c. What is source of fresh water to be blended? No surface water source is allowed.

21. 40 CFR Part 435 Subpart E requires that the permittee document agricultural and wildlife uses of produced water. Provide documentation that the produced water will be used for agriculture or wildlife during periods of discharge. Agriculture and wildlife use includes irrigation, livestock watering, wildlife watering, and other agricultural uses. Agricultural and wildlife use documentation includes (but is not limited to) a certified letter from a landowner(s), a formal written statement from a state, federal or local resource management agency, or a formal written statement with supporting documentation from a natural resources or environmental professional accompanied by the credentials of the natural resources or environmental professional. Agriculture and wildlife use documentation must be provided for each outfall included in the application. Agricultural and wildlife certification must be submitted for each outfall's discharge, and must have original signatures.

Facilities permitted prior to June 10, 2002 are exempt from the above requirement. The Wyoming Game and Fish Department has determined that discharges of produced water from WYPDES-permitted oil production units in Wyoming, *existing as of June 10, 2002*, are being used to enhance wildlife propagation and habitat.

☐ This facility was WYPDES or NPDES permitted prior to June 10, 2002
☐ Documentation of beneficial use is enclosed

22. The Water Quality Division (WQD) encourages the applicant to obtain and maintain an Electronic Discharge Monitoring (eDMR) account. This is in accordance with the EPA Electronic Reporting Rule, which requires all data to be submit be electronically beginning in 2020. Information on how to obtain an eDMR account can be found on the DEQ website: http://deq.wyoming.gov/admin/e-portal/. Information on how to use the eDMR application can be found on the WQD website: http://deq.wyoming.gov/wqd/edmr/.

23. The applicant may submit any optional information the applicant wishes to have considered.

Authorized signatories for this application are the following:	
For corporations:	*A principal executive officer of at least the level of vice president, or the manager of one or more manufacturing, production, or operating facilities, provided the manager is authorized to make management decisions which govern the overall operation of the facility from which the discharge originates.*
For partnerships:	*A general partner.*
For a sole proprietorship:	*The proprietor.*
For a municipal, state, federal or other public facility:	*Either a principal executive officer or ranking elected official.*

I certify under penalty of law that this document and all attachments were prepared under my direction or supervision in accordance with a system designed to assure that qualified personnel properly gather and evaluate the information submitted. Based on my inquiry of the person or persons who manage the system, or those persons directly responsible for gathering the information, the information submitted is to the best of my knowledge and belief, true, accurate, and complete. Additionally, I certify that I have secured and shall maintain permission for Department of Environmental Quality personnel and their invitees to access the permitted facility, including (i) permission to access the land where the facility is located, (ii) permission to collect resource data as defined by Wyoming Statute § 6-3-414, and (iii) permission to enter and cross all properties necessary to access the facility if the facility cannot be directly accessed from a public road. I am aware that there are significant penalties for submitting false information, including the possibility of fine and imprisonment for knowing violations.

______________________________	______________________________
Printed Name of Person Signing	Title
______________________________	______________________________
Signature of Applicant	Date
______________________________	______________________________
Telephone	Fax

Section 35-11-901 of Wyoming Statutes provides that:

*All permit applications must be signed in accordance with 40 CFR Part 122.22, “for” or “by” signatures are not acceptable.

Section 35-11-901 of Wyoming Statutes provides that:

Any person who knowingly makes any false statement, representation, or certification in any application ... shall upon conviction be fined not more than $10,000 or imprisoned for not more than one year, or both.

Mail this application to:

WYPDES Permits Section
Department of Environmental Quality/WQD
200 W. 17th Street, Suite 400
Cheyenne, WY 82002

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Wyoming Statute 35-11-312 was revised to require discharge permit fees be paid prior to permit issuance. Therefore, payment of permit fees must be accompanied with the application. Any application received without proper fee payment will be returned.

Individual permits are issued for a period of five years. A check for $500 per permit must be included with all applications for new permits and renewals for individual WYPDES permits.

I have enclosed a check for $______________

Check Number ________________

For Agency Use Only

Date Check Received _____________________

Check Amount $_______ **Check #** ___________

Permit Term _____________________

Approval ____________________

APPENDIX 3-C: Table on Analytical Methods (Oetjen et al.)

Source: Oetjen, Karl, Cloelle G.S. Giddings, Molly McLaughlin, Marika Nell, Jens Blotevogel, Damian E. Helbling, Dan Mueller, and Christopher P. Higgins. 2017. "Emerging Analytical Methods for the Characterization and Quantification of Organic Contaminants in Flowback and Produced Water." *Trends in Environmental Analytical Chemistry* 15 (July): 12–23, [https://doi.org/10.1016/j.teac.2017.07.002.](https://doi.org/10.1016/j.teac.2017.07.002)

Sampling equipment, preservation techniques, suggested analytical methods for target analytes found in O&G waters.

Target Analyte(s)	Function / Occurrence	Sampling Requirements	Pre-treatment Requirements	Suggested Analytical Instrument(s) and Method (if available)	References
Aldehydes	Biocide, transformation product of biocides, corrosion inhibitor	Glass, store at 2-6°C, acidify to pH < 5, derivatization is required so avoid over acidifying	Derivatize with 2,4-dinitrophenylhydrazine	Formaldehyde and small molecular weight aldehydes by GC with various possible detectors (FID, MS), higher molecular weight aldehydes by LC-UV	21,98-100
Glutaraldehyde	Biocide	Glass, store at 2-6°C, acidify pH <5 to avoid base-catalyzed autopolymerization, avoid overacidifying if subsequent derivatization is chosen	Derivatize with 2,4-dinitrophenylhydrazine (recommended approach)	LC-UV, LC-QToF-MS	29,37,98,101
Quaternary Ammonium and Phosphonum Compounds/Salts	Biocide, clay stabilizer, corrosion inhibitor, surfactant	Glass, store at 2-6°C, glassware needs to be pretreated to avoid analyte loss by adsorption to surface active sites on the glassware	None	LC-QToF-MS, Ion Chromatography	21,37,96,102
DBNPA	Biocide	Glass, store at 2-6°C, acidify pH < 5 (half-life of 67 days at pH=5, possibly larger at lower pH), if hydrolysis occurs (occurs readily above pH 8.5) then hydrolysis products are fairly stable and include dibromoacetic acid and dibromoacetonitrile.	None	LC-MS for DBNPA and dibromoacetic acid, GC-Electron Capture Detector (ECD)for dibromoacetonitrile	16,103

Target Analyte(s)	Function / Occurrence	Sampling Requirements	Pre-treatment Requirements	Suggested Analytical Instrument(s) and Method (if available)	References
Stable Formaldehyde generating biocides/Electrophilic biocides (Bronopol, Dazomet)	Biocide	Glass, store at 2-6°C, Dazomet most stable at pH=7, half-life decreases in acidic and basic conditions; THPS can experience base catalyzed hydrolysis so acidify to pH < 5; Bronopol is stable (half-life of 1.5-2 years) at pH 6, 20°C	None	LC-MS/MS; GC-NPD for Dazomet following EPA Method 1659	29,98,104
Unstable Formaldehyde generating biocides/Electrophilic biocides (Trimethyloxazlidine (TMO) and Dimethyloxazlidine (DMO))	Biocide	Glass, store at 2-6°C, TMO and DMO are unstable and hydrolyze rapidly (half-life minutes to seconds). Thus, once dissolved in water, DMO and TMO parent compounds are no longer detectable. Hydrolysis products are formaldehyde and 2-amino-2-methyl-1-propanol (AMP)	Derivatize with 2,4-dinitrophenylhydrazine for formaldehyde analysis.	The technical grade active ingredient can be determined by the use of GC method. When uncombined, formaldehyde is present, and the difference between the amount of 2-amino-2-methyl-1-propanol added to the sample and the amount found after is calculated as uncombined formaldehyde.	30
Ethoxylated and Propoxylated Alcohols, substituted and unsubstituted (PEGs, LAEs, etc.)	Surfactants, solvent	Amber glass, preserve with sodium azide to prevent biodegradation	None	LC-MS/MS	38
Nonylphenol	Transformation product	Amber glass, store at 0-4°C, to preserve adjust to pH = 2 using H_2SO_4, extract within 28 days of sampling and analyze extract within 40 days, extract can be stored indefinitely at <0°C [ASTM-D7065]	LLE with methylene chloride	Standard method ASTM-D7065, GC-MS, HPLC, GCxGC-ToF-MS	105–107
Small MW amines/Short chain amines/Di- and triamines	Surfactant, crosslinker, breaker, radical initiator, complexing agent, solvent	Sample in glass, store at 2-6°C	None	GC-MS	3,20

Target Analyte(s)	Function / Occurrence	Sampling Requirements	Pre-treatment Requirements	Suggested Analytical Instrument(s) and Method (if available)	References
Large MW amines/long chain amines/fatty amines	Surfactant, crosslinker, breaker, radical initiator, complexing agent, solvent	Sample in glass, store at 2-6°C	None	LC-QToF-MS, LCMS-IT-ToF	3,9,21
Biopolymers (Guar Gum)	Gel forming agent	Sample in glass, store at 2-6°C	If filtering sample, determine the efficiency after filtering or use a large filter (> 0.45µm) since molecules are so large	Measured via chemical oxygen demand; Size Exclusion Chromatography, LC-QToF-MS	9,37,108
Large Polymers (ex: Polyacrylamide, Polyacrylic acid)	Friction reducers, scale inhibitors	Sample in glass, store at 2-6°C	If filtering sample, determine the efficiency after filtering or use a large filter (> 0.45µm) since molecules are so large	Size Exclusion Chromatography	9,101
Acrylamide	By-product of friction reducer	Sample in glass, store at 2-6°C	SPE may be necessary	LC-MS/MS; HPLC-UV following EPA Method 8316	91
Carboxylic acids	Scale inhibitors	Sample in glass, store at 2-6°C	None	Small molecular weight carboxylic acids by IC, higher molecular weight aldehydes by LC-MS	109–111
Ethylene glycol	Corrosion Inhibitor, Cross linker	Sample in glass, store at 2-6°C	See EPA Method 8015, LLE may be needed to concentrate samples or to transfer analyte to non-aqueous phase	GC-FID, EPA Method 8015; GC-MS	112,113
Isopropanol	Corrosion Inhibitor, product stabilizer/winterizing agent	Sample in glass, store at 2-6°C, sample should have no headspace, PTFE caps to prevent out-gassing	See EPA Methods 8015/8260b, LLE may be needed to concentrate samples or to transfer analyte to non-aqueous phase	GC-MS, EPA Method 8260B; GC-FID, EPA Method 8015	23,113
Acetone	Solvent	Glass bottle, collect with no headspace, PTFE caps to prevent out-gassing	See EPA Methods 8015/8260b, LLE may be needed to concentrate samples or	GC-MS, EPA Method 8260B; GC-FID, EPA Method 8015; GC-MS using a polar column ex: Agilent PoraPLOT U, CPWax 57 CB	114

Target Analyte(s)	Function / Occurrence	Sampling Requirements	Pre-treatment Requirements	Suggested Analytical Instrument(s) and Method (if available)	References
			to transfer analyte to non-aqueous phase		
2-Butoxyethanol	Surfactant	Glass bottle, preserved on ice and with sodium azide	LLE, following modification of USEPA Method 3510C	GC-MS, GCxGC/ToF-MS	40
Polycyclic aromatic hydrocarbons (PAHs), other aromatics	Present in formation water	Sample in glass, store at 2-6°C, HCl or H_2SO_4 to pH < 2	LLE into DCM in the field to prevent degradation, concentration samples; Dilution and SPE	GC-MS, EPA Method 610	17,112
Total petroleum hydrocarbons (TPH)	Present in formation water	Sample in glass, store at 2-6°C, HCl or H_2SO_4 to pH < 2	LLE may be needed to concentrate samples	GC-MS; GC-FID, EPA Method 8015	2
BTEX	Present in formation water	Sample in glass, store at 2-6°C, HCl or H_2SO_4 to pH < 2, For SVOCs and VOCs, no headspace in sample bottle	See EPA Methods 5021/8021/8260 and Orem, 2014. LLE may be needed to concentrate samples	GC-MS; EPA Method 5021; EPA Method 8021; EPA 624	2,35
Heterocyclic compounds	Present in formation water	Sample in glass, store at 2-6°C, HCl or H_2SO_4 to pH < 2	LLE into DCM	GC-MS	28,112
Phenols	Present in formation water	Sample in glass, store at 2-6°C, HCl or H_2SO_4 to pH < 2	LLE into DCM	GC-MS	28,112
Phthalates	Present in formation water	Sample in glass, store at 2-6°C, HCl or H_2SO_4 to pH < 2	LLE into DCM	GC-MS	28,112
DRO	Present in formation water	Sample in glass, store at 2-6°C, HCl or H2SO4 to pH < 2	See EPA Method 8015, LLE may be needed to concentrate samples or to transfer analyte to non-aqueous phase	GC-FID, EPA Method 8015	2,12,115
GRO	Present in formation water	Sample in glass, store at 2-6°C, HCl or H_2SO_4 to pH < 2	See EPA Method 8015/8021, LLE may be needed to concentrate samples or to transfer analyte to non-aqueous phase	GC-FID, EPA Method 8015; EPA Method 8021	2,12,116,117

Target Analyte(s)	Function / Occurrence	Sampling Requirements	Pre-treatment Requirements	Suggested Analytical Instrument(s) and Method (if available)	References
VOCS	Present in formation water	Sample in glass, store at 2-6°C, HCl or H_2SO_4 to pH < 2, For SVOCs and VOCs, no headspace in sample bottle	See EPA Method 8260b, LLE may be needed to concentrate samples or to transfer analyte to non-aqueous phase	GC-MS, EPA Method 8260B; EPA 624	2,9,12,35,113,117
SVOCs	Present in formation water	Sample in glass, store at 2-6°C, HCl or H_2SO_4 to pH < 2, For SVOCs and VOCs, no headspace in sample bottle	See EPA Method 8270c, LLE may be needed to concentrate samples or to transfer analyte to non-aqueous phase	GC-MS, EPA Method 8270C	2,9,12,118

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APPENDIX 3-D: Center for Responsible Shale Development: Standard One

CENTER FOR RESPONSIBLE SHALE DEVELOPMENT

WATER PERFORMANCE STANDARDS

The goal of the water standards is that there be zero contamination of fresh groundwater1 and surface waters.

PERFORMANCE STANDARD 1

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1. Operators shall maintain zero direct or indirect intentional discharges of shale wastewater (including drilling, flowback and produced waters) to surface water except as provided by this Standard.
2. In order to facilitate comprehensive wastewater management programs that consider environmental, safety, health, and economic factors, Operators may send shale wastewater to a Centralized Waste Treatment facility (CWT) for treatment and discharge if the Operator demonstrates the following conditions are satisfied at the CWT:
   a. The CWT has, and is in substantial compliance with, a NPDES discharge permit to treat and directly discharge shale wastewater;
   b. The CWT meets or exceeds a CRSD shale wastewater effluent performance standard to be based on current best available technology designed to prevent the discharge of toxic pollutants in toxic amounts;
   c. The CWT must use best available technology for all fluids discharged. Best available technology requires a combination of distillation and biological treatment, with the addition of reverse osmosis if CRSD determines based on further analysis that it provides protection necessary to ensure effluent quality. CRSD may authorize the use of different technologies or combinations of technologies that provide equivalent or superior treatment;
   d. The CWT adheres to acceptance procedures designed to assure that the wastewater delivered by the Operator is compatible with the other wastes being treated at the facility, treatable by the treatment system, and consistent with the specific waste stream the facility was permitted to treat and discharge;
   e. The CWT does not indirectly discharge wastewater from a CRSD Operator through a POTW.
3. An uncertified Operator must meet the following obligations prior to certification to this Standard and a certified Operator must meet the obligations prior to the use of a new CWT for discharge:
   a. Operator shall review, compile, analyze, and deliver to CRSD, publicly available information pertaining to the CWTs performance and permit compliance to demonstrate that the CWT satisfies Part 2(a).

   b. In order to help assure the permit writer has all information necessary to consider establishing limits on all pollutants in the expected influent, the permitting agency shall be provided the current CRSD list of chemicals believed to occur in the region's wastewater.
   c. In order to confirm the CWT is operating as intended, the Operator shall demonstrate to CRSD that testing at the CWT satisfies the Initial Confirmatory Testing Program or a facility-specific Protocol approved by CRSD.
   d. In order to evaluate the potential for CWT effluent toxicity, Operator shall complete WET Testing pursuant to the WET Testing Program or an alternative facility specific Protocol approved by CRSD.
4. For so long as the Operator delivers shale wastewater to a CWT:
   a. Operator shall conduct effluent monitoring as specified in the CRSD Ongoing Monitoring Program or facility-specific Protocol approved for that CWT by CRSD.
   b. Every six months, Operator shall review, compile, analyze and deliver to CRSD publicly available information about the CWT's performance and permit compliance.
   c. Unless CRSD determines that ongoing WET testing is not necessary, Operator shall complete WET testing at a frequency to be determined in the WET Testing Program or facility-specific Protocol.
5. Operators may not initiate, and will immediately cease, deliveries to a CWT:
   a. If the CRSD Board determines that discharges from the CWT may increase the risk of harm to human health or the environment. This determination may take into account data and reports submitted to CRSD under this standard, deterioration in effluent quality, research to be sponsored by CRSD or by other parties, and/or any other data or available research.
   b. That exhibits substantial non-compliance with its NPDES permit.

Deliveries shall not be resumed until the Operator demonstrates to the satisfaction of CRSD that appropriate corrective measures have been made.

6. Operator reporting under this standard shall be as follows:
   a. Data from all testing and any additional information gathering required under this standard, shall be analyzed, compiled, and submitted to CRSD by the Operator.
   b. Where an operator discovers a potential non-compliance with an existing NPDES discharge permit as part of the monitoring and auditing requirements required under this Standard, the Operator shall immediately report such findings to the CWT, the permitting agency, and CRSD.

Note: This standard does not apply to nor prohibit disposal of wastewater by deep well injection.

[1] "Fresh groundwater" is "water in that portion of the generally recognized hydrologic cycle which occupies the pore spaces and fractures of saturated subsurface materials."

Adopted: August 19, 2013; Amended: December 9, 2014

Technical Guidance

Effluent Monitoring Programs

Wastewater Discharge Standard No. 1

Background

This document provides supporting guidance for implementing the Initial Confirmatory Testing and Ongoing Monitoring Programs required in sections 3.c and 4.a respectively of Standard No. 1. The framework for both programs is presented in the following sections. Final Ongoing Monitoring Protocols specific to conditions and circumstances of the CWT being monitored will be developed by the technical subcommittee and provided to the Standards Committee for approval. In all instances of testing and monitoring, samples will be analyzed by a laboratory that is accredited by the National Environmental Accreditation Program (NELAP).

Initial Confirmatory Testing Program

As noted in the standard, confirmatory sampling of the effluent must be completed at any CWT used for discharge. Representative effluent samples will be collected at the monitoring point specified in the CWT's NPDES permit.

Prior to initiation of sampling activities, a sampling and analysis plan (SAP) shall be developed by the Operator for review and approval by CSSD. The SAP shall detail sample collection and handling procedures including applicable QA/QC samples (field duplicates, trip blanks, and equipment rinsate blanks) and analytical lab(s) selected to perform analysis (if multiple labs are proposed, analyses performed by each lab shall be specified).

Unless modified by CSSD in a facility-specific Protocol, the list of parameters included as part of the initial confirmatory sampling and associated analytical methods are identified in Attachment A. Attachment A may be revised as additional science and knowledge is developed relative to shale wastewater constituents and available and approved analytical methods.

Unless modified by CSSD in a facility-specific Protocol, a minimum of five sampling events will be conducted over an appropriate period (the default period shall be 10 days unless an alternative period is approved by CSSD in the SAP) in order to ensure that discharges sampled are representative of treated effluent typically discharged by the facility being tested. The type of samples collected (grab vs. 24-hour composite) for each sampling event will be based on the monitoring requirements specified in the NPDES permit.

Full laboratory data reports and a summary table of all analytical results will be provided to CSSD following conclusion of the sampling event. Additionally, a summary report will be provided demonstrating that all work was performed in accordance with the applicable testing Program or Protocol and identifying any changes to the field or laboratory protocols that may have resulted in a deviation from expected results, in particularly any QA/QC issues.

Ongoing Monitoring Program

Unless established otherwise in a facility-specific Protocol, all monitoring tests conducted under this subsection will occur on a semi-annual basis, beginning six months after results are finalized for the Initial Confirmatory Testing Program.

Until modified by CSSD, ongoing monitoring will follow the same sampling and analysis procedures as specified in the Initial Confirmatory Testing Program. This includes the list of parameters and associated analytical methods included in Attachment A.

Full laboratory data reports and a summary table of all analytical results will be provided to CSSD following conclusion of the sampling event. Additionally, a summary report will be provided demonstrating that all work was performed in accordance with the applicable testing Program or Protocol and identifying any changes to the field or laboratory protocols that may have resulted in a deviation from expected results, in particular any QA/QC issues.

Attachment A

Analytical Parameters and Analytical Methods

Analysis	Method
TOC	EPA 415.1
Aldehydes	SW-846 8315
VOCs	SW-846 8260B with 20 noninterpretive TICs
SVOCs	SW-846 8270C with 25 noninterpretive TICs
Pentanoic and Hexanoic Acids	8270C-TLS (Library Search)
Organic Acids	SW-846 8015B (mod)
Alcohols	SW-846 8015B (mod)
Glycols	LC/MS/MS 8321AMOD
TPH C8-C40	SW-846 8015B (TPH)
30 ICP Metals	SW-846 6010B
Anions - Sulfate, Chloride, Fluoride, Bromide	EPA 300
Ammonia	EPA 350.2
TDS	SM 2540D
Ra 226 and Ra 228, dissolved, insoluble	EPA 903.1 and 904
Acrylamide	EPA 603
MBAS	Method SM 5540 C-2000
Mercury	Cold Vapor Method EPA 245.7
Nonylphenol	WS-MS-0010
Nitrite	SW-846 9056/A
Nitrate	SW-846 9056/A
Hexavalent Chromium	SM 3500-Cr B-2009
Total Strontium	EPA 200.7
Thallium	EPA 200.8

Revised 2017

CSSD Whole Effluent Toxicity (WET) Test Program
(Including a Modification for Low Ionic Content Effluents)

Standard WET Testing Program Background

WET testing is used to identify effluent toxicity which may be caused by the aggregate and/or synergistic toxic effects of a mixture of pollutants and other water quality parameters. WET testing is required by CSSD Standard 1 in order to evaluate the potential for CWT effluent toxicity. WET testing is also required as a part of ongoing effluent quality monitoring for facilities operating under the standard unless CSSD determines ongoing WET testing is not necessary in a particular case. WET testing will be conducted every six months, beginning six months after results are finalized for the initial WET test, unless CSSD determines another timeline is appropriate.

Specifications

Acute and chronic toxicity tests will be completed using the water flea (Ceriodaphnia dubia) and fathead minnow (Pimephales promelas). An additional chronic test will be completed using the alga Raphidocelis subcapitata (formerly known as Selenastrum capricornutum and Pseudokirchneriella subcapitata). All testing will be conducted in accordance with the following EPA methods [EPA 2002a,b]:

- 2002.0 Ceriodaphnia dubia, acute
- 2000.0 Fathead Minnow, Pimephales promelas, acute
- 1002.0 Daphnia, Ceriodaphnia dubia, survival and reproduction
- 1000.0 Fathead minnow, Pimephales promelas, larval survival and growth.
- 1003.0 Green alga, Selenastrum capricornutum (renamed to Raphidocelis subcapitata and also may be referred to as Pseudokirchneriella subcapitata), growth.

Tests will be conducted at five effluent concentrations using a dilution factor of 0.5 (see, for example, EPA 2002b, p. 204). Testing will be conducted under laboratory specific quality control standard operating procedures (SOPs) which are in conformance with NELAC and US EPA guidelines, where applicable.

Modification for Low Ionic Content Effluents

Background

Some wastewater treatment processes, such as distillation and reverse osmosis, may create effluents that are toxic due to the absence of salts or ions required to support aquatic life (ionic imbalance toxicity [SETAC 2004]). Low ionic content effluents that are expected to fail the **Standard WET Testing Program** may be evaluated for toxicity using this modification. The ionic imbalance toxicity is addressed by adding simple salts to effluent samples prior to testing for whole effluent toxicity. This modification is intended to capture any additional toxicity that might be present due to effluent pollutants.

Modifying Effluents for Ionic Imbalance Toxicity

Prior to preparing test solutions, effluent samples will be modified by the addition of physiologically required ions as specified in the EPA moderately hard synthetic freshwater recipe [EPA 2002a, p. 32]. Otherwise, all other requirements outlined in this Standard WET Testing Program remain the same..

Reporting Requirements

The laboratory should provide the Operator with proof of proper accreditation. The laboratory will provide a final report specifying sampling and testing methods, test conditions, amended effluent and test solution properties, materials, results, statistical determination of organism survival and reproduction rates at the established effluent concentrations, any unforeseen laboratory protocol deviations, any results that indicate a potential effluent toxicity, and conclusions and recommendations based on results. . In the event results or laboratory conclusions indicate a potential effluent toxicity, the appropriate EPA guidance documents will be followed, unless CSSD establishes otherwise, and CSSD will assist as needed with detailing the proper procedures for ongoing analysis.

References

EPA 2002a, "Methods for Measuring the Acute Toxicity of Effluents and Receiving Waters to Freshwater and Marine Organisms," Method Manual EPA-821-R-02-012, Fifth edition, U.S. Environmental Protection Agency, Office of Water, Washington, DC , available at: http://water.epa.gov/scitech/methods/cwa/wet/upload/2007_07_10_methods_wet_disk2_atx.pdf.

EPA 2002b, "Short-Term Methods for Estimating the Chronic Toxicity of Effluents and Receiving Water to Freshwater Organisms," Method Manual EPA-821-R-02-013, U.S. Environmental Protection Agency, Office of Water, Washington, DC, Fourth edition, available at: http://water.epa.gov/scitech/methods/cwa/wet/upload/2007_07_10_methods_wet_disk3_ctf.pdf.

SETAC 2004, "Whole Effluent Toxicity Testing: Ion Imbalance," Technical Information Sheet, Society of Environmental Toxicology and Chemistry, Pensacola, FL, available at: https://www.setac.org/resource/resmgr/publications_and_resources/tip-ion.pdf.

APPENDIX 3-E: Current Treatment Technologies and Known Removal of Constituent **Classes**

TREATMENT TECHNOLOGY	VALIDATION	TDS RANGE	SOLIDS REMOVAL	ORGANICS REMOVAL	METALS REMOVAL	TDS REMOVAL	WATER/ WASTE RECOVERY	ENERGY DEMAND	CITATIONS
OIL/WATER/SAND SEPARATOR	Mature	All	Suspended	Insoluble organics; no removal of dissolved organics	None	None	High Water Recovery; Solids Management Needed	Low	Arthur et al., 2005 (ALL Consulting); RPSEA, 2016
NOTES	No chemicals required, high construction cost and footprint, but operation and maintenance costs are low. Removals of Oil Droplets > 150 um, 33-68% total suspended solids removal, and 16-45% chemical oxygen demand								
HYDROCYCLONE	Mature	All	Suspended	Insoluble organics; no removal of dissolved organics	None	None	High Water Recovery; Solids Management Needed	Low	Van den Broek et al., 2013; Jimenez et al., 2018; DOE NETL, Xu et al., 2016
NOTES	Oil/Water/Gas separation as well as solids removal. Little to no removal of dissolved constituents. Particles with sizes > 5 to 15 um								
SETTLING	Mature	All	Suspended	Insoluble organics; no removal of dissolved organics	None	None	High Water Recovery; Solids Management Needed	Low	Drewes et al., 2009
NOTES	No chemical requirements, but typically require a large footprint and environmental mitigation to protect wildlife. Considerations for evaporation, and volatilization of hydrocarbons should be taken. Particle removals for > 0.5 um								
DISSOLVED AIR/GAS FLOTATION	Mature	All	Suspended	Insoluble organics; no removal of dissolved organics	Minimal (oxidation of select metals)	None	High Water Recovery; Solids Management Needed	Low to Moderate	Goududey and Kaushal, 2013; Haarhoff and Edzwald, 2013; Çakmakce 2008; Hayes and Arthur; Drewes et al., 2009.

TREATMENT TECHNOLOGY	VALIDATION	TDS RANGE	SOLIDS REMOVAL	ORGANICS REMOVAL	METALS REMOVAL	TDS REMOVAL	WATER/ WASTE RECOVERY	ENERGY DEMAND	CITATIONS
NOTES	Clarification process aimed at removing suspended solids and emulsified oil. High salinity does impact DAF since density, dynamic viscosity and surface tension are higher for high concentration of soluble species. Estimated costs $0.60/m3 (Çakmakce et al., 2008). Removals of Oil up to 93% removal, suspended solids removal (with [25 um] or without flocculants [3-5 um).								
MEDIA FILTRATION	Mature	All	Suspended	Insoluble organics; no removal of dissolved organics	None	None	High Water Recovery, but backwash water needs to be managed and disposed	Low	Xu et al., 2016
NOTES	Varies medias can be used for filtration and is commonly used in both municipal and produced water treatment. particle removals from 1–10 um and 90% removal of oil								
CHEMICAL COAGULATION/ FLOCCULATION	Mature	All	Suspended/ Dissolved	Insoluble organics; and variable removal of dissolved organics	Possible with lime/softening (heavy metals), oxidation (arsenic and mercury), or other aids that can be added during flocculation	None	High Water Recovery; Solids Management Needed	Low	Rosenblum et al., 2016; Zhou et al., 2000; Houcine M., 2002; Frankiewicz and Gerlach, 2000
NOTES	Clarification process that uses metal salts to create charged surfaces to coalesce particles to facilitate settling. Demonstrated in low and high-TDS produced waters and been shown to remove some DOC. Solids and oil removals up to 97% and 92%, respectively. TOC removals for unconventional produced water of 15% reported, but coagulant dose dependent.								
ELECTRO-COAGULATION	Emerging	All	Suspended/ Dissolved	Insoluble organics; and variable removal of dissolved organics	Variable removal; but can be combined with softening processes for enhanced removals	None	High Water Recovery; Solids Management Needed	Moderate	Chaturvedi S., 2013; Esmaeilirad et al., 2015; Malakootian et al., 2010; Ezechi et al., 2014
NOTES	Clarification process that uses an electrochemical process to release free metals from sacrificial anodes (metal sheets) to generate coagulants that remove contaminants by precipitation and flotation. Chemical softening can significantly improve EC efficiency.								

TREATMENT TECHNOLOGY	VALIDATION	TDS RANGE	SOLIDS REMOVAL	ORGANICS REMOVAL	METALS REMOVAL	TDS REMOVAL	WATER/ WASTE RECOVERY	ENERGY DEMAND	CITATIONS
BIOLOGICALLY ACTIVATED FILTRATION (BAF)	Mature (in municipal applications, but not for produced water)	~ 60 g/L	Suspended/ Dissolved	High soluble organics removal	Minimal removal	None	High Water Recovery, but backwash water needs to be managed and disposed	Low	Riley et al., 2018; Riley et al., 2017; Freedman et al., 2017
NOTES	Biological process that uses a permeable media with bound microbes upon it to remove suspended (media) and dissolved (microbes) constituents. BAF is most effective at lower TDS, yet recent research is showing its capabilities in higher TDS applications (>50,000 mg/L).								
ACTIVATED SLUDGE PROCESS (BIOLOGICAL)	Mature (in municipal applications, but not for produced water)	~ 60 g/L	Dissolved	High soluble organics removal	Minimal removal	None	High Water Recovery, but need to manage a solids stream	Low to Moderate	Drewes, 2009; Tellez, 2002; Lu and Wei, 2011
NOTES	Aerobic biological treatment that uses suspended microbes that form settleable flocs. Large space is required for aeration tank and clarifier. Salinity can negatively impact activated sludge, by slowing biological processes and floc formation (settling of solids). Energy demand should be a consideration at around 2 kWh/bbl (Tellez, 2002)								
MEMBRANE BIOREACTOR	Mature (in municipal applications, but not for produced water)	~ 60 g/L	Suspended/ Dissolved	High soluble organics removal	Minimal removal	None	High Water Recovery, but need to manage a solids stream	Low to Moderate	Rahman and Al-Malack, 2006; Viero et al., 2008; Kose et al., 2012
NOTES	Membrane bioreactor modifies conventional activated sludge using a submerged microfiltration or ultrafiltration membrane, to draw water through, creating a highly clarified effluent. Chemicals are typically needed for membrane cleaning. Small footprint and often mobile.								
POLYMERIC MICROFILTRATION	Mature	All	Suspended	Insoluble organics; and minimal removal of dissolved organics	Minimal removal	None	High Water Recovery, but need to manage rejection and backwash streams	Moderate	CSM Technical Assessment, 2009; Cakmackce et al., 2008;
NOTES	Largest pore size (0.1-3um) and generally used for suspended solids and turbidity removal. Operates at low pressures (1-30psi), and is often used as a pre-treatment step for NF or RO.								

TREATMENT TECHNOLOGY	VALIDATION	TDS RANGE	SOLIDS REMOVAL	ORGANICS REMOVAL	METALS REMOVAL	TDS REMOVAL	WATER/ WASTE RECOVERY	ENERGY DEMAND	CITATIONS
POLYMERIC ULTRAFILTRATION	Mature	All	Suspended	Insoluble organics; and minimal removal of dissolved organics	Minimal removal	None	High Water Recovery, but need to manage rejection and backwash streams	Moderate	Igunnu and Chen, 2014;He and Jiang, 2008; Lia et al., 2006; Bilstad and Espedal, 1996
NOTES	Pore size of 0.01 to 0.1 um and allows for removal of macromolecules, and has been shown to be effective for significant oil removal and large dissolved constituents. Often used as a pretreatment step for RO in produced water treatments								
CERAMIC MEMBRANES (MF OR UF)	Mature	All	Suspended	Insoluble organics; and minimal removal of dissolved organics	Minimal removal	None	High Water Recovery, but need to manage rejection and backwash streams	Moderate	Mulder, 2003; Lobo et al., 2006; Xu et al., 2016
NOTES	Ceramic ultrafiltration membranes are made of oxides, nitrides, or carbides of metals. Ceramic membranes are much more resilient than polymeric membranes are mechanically stronger, as well as chemically and thermally stronger. They can also achieve higher flux rates.								
NANO-FILTRATION	Mature (for non O&G operations)	~ 40 g/L	Suspended/ Dissolved	Insoluble organics; and significant dissolved organics	Partial to significant removal; highly dependent upon feed water composition and operation conditions	Partial to significant removal: highly dependent upon feed water composition and operation conditions	Water recovery can vary from high to moderate	Moderate to High	Bellona and Drews, 2005; Long Beach Water Department, 2006; Ventresque et al., 1997; Riley et al., 2018; Xu et al., 2016
NOTES	Pressure-driven membrane process that remove constituents down to 0.0001 um. RO is frequently used for the desalination of seawater (~30,000 mg/L), but the treatment of higher TDS waters can be challenging due to the energy associated with desalination								
FORWARD OSMOSIS	Emerging	~140 g/L	Suspended/ Dissolved	Insoluble organics; and significant dissolved organics	Partial to significant removal; highly dependent upon feed water	Partial to significant removal: highly dependent upon feed	Water recovery can vary from high to moderate	High	Martinetti C., 2007; Cath et al., 2007; Maltos et al., 2018; Bell et al., 2017

TREATMENT TECHNOLOGY	VALIDATION	TDS RANGE	SOLIDS REMOVAL	ORGANICS REMOVAL	METALS REMOVAL	TDS REMOVAL	WATER/ WASTE RECOVERY	ENERGY DEMAND	CITATIONS
					composition and operation conditions	water composition and operation conditions			
NOTES	Emerging osmotically driven membrane technology, which has been employed for produced water treatment with some success								
REVERSE OSMOSIS	Mature	~ 50 g/L	Suspended/ Dissolved	Insoluble organics; and significant dissolved organics	High removal	High Removal	Water recovery can vary from high to moderate	High	Spiegler and Kedem, 1966; Dischinger et al., 2018; Riley et al., 2018; Mondal; Xu et al., 2016
NOTES	Pressure-driven membrane process that remove constituents down to 0.0001 um. RO is frequently used for the desalination of seawater (~30,000 mg/L), but the treatment of higher TDS waters can be challenging due to the energy associated with desalinating waters with TDS levels higher than seawater(). RO has been used to treat Produced water								
ELECTRODIALYSIS	Mature	~8,000 mg/L	Dissolved	None	High removal from low concentration influent	High removal from low concentration influent	Water recovery can vary from high to moderate (70-90%)	High	Mickley M.C., 2006; Bilat, 2001; Hayes et al., 2006; Sirivedhin et al., 2004
NOTES	Electrochemical charge driven separation, where dissolved ions are separated from water using ion permeable membranes under an electrical potential gradient								
THERMAL DISTILLATION	Mature	All. Ideal for operations >30,000 mg/L	Dissolved	High removal of non-volatile organic constituents	High removal	High removal	Water recovery can vary from high to moderate	High	Shannon et al., 2010; Gregory et al., 2011
NOTES	Utilization of heat to accelerate distillation								
MEMBRANE DISTILLATION	Emerging in produced water space	Varies, ideal for operations >30,000 mg/L	Dissolved	High removal of non-volatile organic constituents	High removal	High removal	Water recovery can vary from high to moderate	High	Macedonio et al., 2014; Adham et al., 2013; Cath et al., 2004

TREATMENT TECHNOLOGY	VALIDATION	TDS RANGE	SOLIDS REMOVAL	ORGANICS REMOVAL	METALS REMOVAL	TDS REMOVAL	WATER/ WASTE RECOVERY	ENERGY DEMAND	CITATIONS
NOTES	Thermally driven membrane separation process, which utilizes low-grade heat to enable mass transport through a membrane								
EVAPORATOR / CRYSTALLIZER	Mature	All, Best at >30,000 mg/L	Dissolved	High removal of non-volatile organic constituents	High Removal	High Removal	Varies from high to moderate	High in the case of crystallizer, while evaporation ponds are low in energy	Heins, 2005; NRC, 2004
NOTES	Evaporation utilizes solar energy to evaporate water, while crystallizers typically use vacuum to accelerate evaporation								
MULTI-EFFECT DISTILLATION	Mature, but emerging in produced water	All, best at >30,000 mg/L	Dissolved	High removal of non-volatile organic constituents	High Removal	High removal	Varies from high to moderate	High	Peterson and Zhao, 2006; Hamed, 2004; Bruggen and Vandecasteele, 2002
NOTES	Multi-Effect Dist. Is the application of sufficient energy to raise the incoming waters temperature to its boiling point, followed by additional energy to achieve the heat of vaporization to transform the water to steam, that is condensed in the final step								
ADSORPTION	Mature	Nearly all, but can depend on the constituent being absorbed	Dissolved	Can be high, but declines overtime as active sites of the adsorptive material are consumed	Can be high, but declines overtime as active sites of the adsorptive material are consumed	Limited	High Water Recovery, but need to manage backwash stream and disposal of media upon exhaustion	Low	Spellman, 2003; DOE NETL; Rosenblun et al., 2016; Younker and Walsh, 2014; Doyle and Brown, 2000; Drewes, 2009 ; Lobo et al., 2016
NOTES	Adsorption of chemicals can be accomplished using various materials such as: zeolites organoclays and activated carbon. Capable of total organic carbon, hydrocarbons, heavy metals, and many other constituents. Media can be regenerated, but media ultimately has a life span and must be disposed of after that.								
ION EXCHANGE	Mature	All	Dissolved	Can be high, but declines overtime as active sites of the adsorptive	Can be high, but declines overtime as active sites of the adsorptive	Limited	High Water Recovery, but need to manage backwash stream and	Low	Nadav, 1999; Letterman, 1999; ALL Consulting, 2006

TREATMENT TECHNOLOGY	VALIDATION	TDS RANGE	SOLIDS REMOVAL	ORGANICS REMOVAL	METALS REMOVAL	TDS REMOVAL	WATER/ WASTE RECOVERY	ENERGY DEMAND	CITATIONS
				material are consumed	material are consumed		disposal of media upon exhaustion		
NOTES	Adsorption of chemicals can be accomplished using various materials such as: zeolites organoclays and activated carbon. Capable of total organic carbon, hydrocarbons, heavy metals, and many other constituents. Media can be regenerated, but media ultimately has a life span and must be disposed of after that.								
OZONE	Mature (in municipal applications, but not for produced water)	All	Dissolved	Varies, constituent specific	Select	None	Water recovery is high	Moderate	Langlais, Reckhow, Brink, 1991; Fakhru'l-Razi et al., 2009
NOTES	Ozone is typically generated by passing O2 by high voltages, to generate the highly reactive ozone species O3, which is used for disinfection and organic constituent removal in water and some wastewater treatment applications. Typically used as a final polishing step in treatment trains								
FENTON	Mature (in municipal applications, but not for produced water)	All	Dissolved	Varies, constituent specific	None	None	Water recovery is high	Low	Fakhru'l-Razi et al., 2009; Lester et al., 2015; Nidheesh and Gandhimathi, 2012
NOTES	Utilizes iron and hydrogen peroxide to generate hydroxyl radicals that can be used a for the oxidation of organic constituents in the water								
UV-H2O2	Mature (in municipal applications, but not for produced water)	All	Dissolved	Varies, constituent specific	None	None	Water recovery is high	Low - Moderate	Parson, 2004; Chong et al., 2010; Oturan and Aaron, 2014
NOTES	UV-H2O2 utilizes UV light to generate hydroxyl radicals by cleaving the oxygen to oxygen bond, which can be used for the oxidation of organic constituents in water. Typically used as a final polishing step in treatment trains								

TREATMENT TECHNOLOGY	VALIDATION	TDS RANGE	SOLIDS REMOVAL	ORGANICS REMOVAL	METALS REMOVAL	TDS REMOVAL	WATER/ WASTE RECOVERY	ENERGY DEMAND	CITATIONS
ELECTROCHEMICAL OXIDATION	Mature (in municipal applications, but not for produced water)	All	Dissolved	Varies, constituent specific	None	None	Water recovery is high	Moderate	Huitle and Panizza, 2018; Garcia-Segura et al., 2018; Alberto Martinez-Huitle et al., 2014
NOTES	Direct electrochemical oxidation occurs by transferring electrons at an electrode surface without participation of other substances, while the indirect electrochemical oxidation uses some electroactive species generated at an anode surface that helps shuttle electrons between the electrode and the organic constituents								

APPENDIX 3-F: Module 3 Literature Review Methodologies

Methodology for Search Logic

We developed and refined search terms to identify current state of research (within the last 15 years) to address the following background questions: (1) what are the requirements and/or guidelines on water quality for degraded water use in industry, agriculture, or wildlife; (2) what do we know about water quality of produced water; and (3) what are the potential environmental and human health impacts from improper disposal or produced water (e.g., spills or minimal treatment)? After the initial review of the literature, questions 1 and 2 were expanded to include specific examples of produced water being used outside oil and gas operations and lead to refining our search logic. The following search logic strings were used in this literature review:

Question	**Database**	**Search Logic**
What are the requirements and/or guidelines on water quality for degraded water use in industry, agriculture, or wildlife?	Web of Science	(Reclaimed water OR Water reclamation OR Degraded water OR Nonpotable water OR Impaired quality) AND (Guidelines OR Criteria) AND (Livestock OR Irrigation OR Landscape OR Industrial OR Wetland OR Groundwater recharge OR Managed underground storage OR Saltwater intrusion OR Beneficial use OR Aquaculture OR Agricultur* OR Crop)
What do we know about water quality of produced water?	Web of Science	(Oil OR Gas OR Hydraulic fractur* OR Frack* OR Frac* OR Unconventional OR Tight OR Shale) AND ("Produced waters" OR "Produced water" OR Flowback OR "oilfield Brine" OR wastewater)
Where has produced water been employed outside oil and gas operations?	Web of Science	(“produced water” OR “produced waters” OR flowback) AND (Livestock OR Irrigation OR Landscape OR Industrial OR Wetland OR Groundwater recharge OR Managed underground storage OR Saltwater intrusion OR Beneficial use OR Aquaculture OR Agricultur* OR Crop)
What are the potential environmental and human health impacts of produced water?	Various	(Oil OR Gas OR Petroleum OR Hydraulic Fracture* OR Frack* OR Unconventional OR Tight OR Shale) AND (environment* OR spill OR exposure) AND (tox* OR health* OR hazard* OR risk OR endocrine* OR crop* OR human OR wildlife OR livestock OR fish*)

Literature Review Results

A. Degraded Water

This literature review aims to (a) identify scientific reports on environmental and human health impacts of produced water, and (b) define knowledge and gaps in the literature pertaining to chemical contaminants of concern, relevant exposures, and human and environmental health impacts. Considering the scope of this review, peer-reviewed publications from the Web of Science database was included. Altogether, 368 articles were initially screened and evaluated through subject matter expert review. Additional publications were included through hand-searching and expert knowledge of the literature for a total of 27 papers.

B. Produced Water Quality

This literature review aims to (a) identify literature that characterize produced water, and (b) define knowledge and gaps in the literature on produced water quality. Considering the scope of this review, peer-reviewed publications and grey literature from the Web of Science database was included. Altogether, 2,261 records were initially screened through subject matter expert review. Additional publications were included through hand-searching and expert knowledge of the literature for a total of 96 papers.

C. Produced Water Reuse

This literature review aims to identify ways that produced water has been used, or studied for use, outside oil and gas operations. Considering the scope of this review, peer-reviewed and grey literature from the Web of Science database was included. Altogether, 393 articles were initially screened and evaluated through subject matter expert review. Additional publications were included through hand-searching and expert knowledge of the literature for a total of 35 papers.

D. Environmental and Health Hazards

Considering the scope of this review, peer-reviewed publications from either Pubmed or Web of Science databases were included. Altogether, 2,111 articles were initially evaluated through subject matter expert review, and 300 articles were judged to be relevant to the search topic (see attached bibliography). Comprehensive quality assessment of the article selection was out of the scope of this review. Despite its focus on onshore applications, environmental impacts reported for offshored produced water were evaluated where appropriate.

APPENDIX 3-G: Module 3 Literature Review Bibliographies

Degraded Water Reuse

Adewumi, J. R., A. A. Ilemobade, and J. E. van Zyl. "Minimizing risks in wastewater reuse: proposed operational principles and guidelines for South Africa." *Journal of Water Reuse and Desalination* 2.4 (2012): 227-238.

Anderson, L., et al. "Water reclamation and reuse." *Water Environment Research* 86.10 (2014): 1297-1313.

Bickerton, B., et al. "Water reclamation and reuse." *Water Environment Research* 83.10 (2011): 1383-1396.

Blaine, A., et al. "Perfluoroalkyl Acid Uptake in Lettuce (*Lactuca sativa*) and Strawberry (*Fragaria ananassa*) Irrigated with Reclaimed Water." *Environmental Science & Technology* 48 (24): 14361–68.

Chen, Zhuo, et al. "Analysis of Sydney's recycled water schemes." *Frontiers of Environmental Science & Engineering* 7.4 (2013): 608-615.

Crook, James, and Rao Y. Surampalli. "Water reclamation and reuse criteria in the US." *Water Science and Technology* 33.10-11 (1996): 451-462.

Di Toro, D.M., McGrath, J.A., Stubblefield, W.A.2007. Predicting the toxicity of neat and weathered crude oil: toxic potential and the toxicity of saturated mixtures. *Environ Toxicol Chem*. 2007 Jan;26(1):24-36.

Follett, Matthew, et al. "Water reclamation and reuse." *Water Environment Research* 82.10 (2010): 1337-1347.

Gonzalez-Serrano, E., et al. "Cost of reclaimed municipal wastewater for applications in seasonally stressed semi-arid regions." *Journal of water supply: research and technology-Aqua* 54.6 (2005): 355-369.

Goodwin, D., et al. "Applying the water safety plan to water reuse: Towards a conceptual risk management framework." *Environmental Science: Water Research & Technology* 1.5 (2015): 709-722.

Hamilton, Andrew J., et al. "Is the risk of illness through consuming vegetables irrigated with reclaimed wastewater different for different population groups?" *Water science and technology* 54.11-12 (2006): 379-386.

Hamilton, Andrew J., et al. "RIRA: A tool for conducting health risk assessments for irrigation of edible crops with recycled water." *Computers and electronics in agriculture* 57.1 (2007): 80-87.

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