PRODUCED WATER REPORT

Regulations & Practices Updates

GROUNDWATER PROTECTION COUNCIL

Published:
May 2023

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Acronyms

ADEE Arkansas Department of Energy and Environment
AOGC Arkansas Oil & Gas Commission
AOI Area of Interest
AOP Advanced Oxidation Processes
AOR Area of Review
ASR Aquifer Storage and Recovery
ATP adenosine triphosphate
bbls/day Barrels per day
Bcf/d Billion Cubic Feet per Day
BRInE Brine Research Instrumentation and Experimental
bwpd barrels of water per day
BWRO Brackish Water Reverse Osmosis
$CaCl_2$ Calcium Chloride
CBM Coalbed Methane
CFR Code of Federal Regulations
COGCC Colorado Oil & Gas Conservation Commission
CPWC Colorado Produced Water Consortium
CWA Clean Water Act
DAF Dissolved Air Flotation
DBA Design/Build Agreement
DOE U.S. Department of Energy
DOGRM Division of Oil & Gas Resource Management
DWTR drinking water treatment residuals
ED electrodialysis
EDF Environmental Defense Fund
EIA Energy Information Administration
EOR Enhanced Oil Recovery
EPA U.S. Environmental Protection Agency
ESG Environmental, Social, Governance
Fe Iron
FECM DOE Office of Fossil Energy and Carbon Management
FO Forward Osmosis
FR Friction Reducer
GAC Granular Activated Charcoal
GHCR Geologic Homogenization Conditioning and Reuse
GWh Gigawatt hours
GWPC Ground Water Protection Council
H_2S - Hydrogen Sulfide
HB House Bill
KCC Kansas Corporation Commission
KDHE Kansas Department of Health and Environment
KGS Kansas Geological Survey
Km3 cubic kilometers
KPI Key Performance Indicators
kWH kilowatt Hours
LADNR Louisiana Department of Natural Resources
LBNL Lawrence Berkeley National Laboratory
LiCl lithium chloride
LNG Liquefied Natural Gas
LTDis Low Temperature Distillation
M Magnitude Earthquake (M4.0+)
MM Million
MBOGC Montana Board of Oil and Gas Conservation
MD Membrane Distillation
MED Multiple Effect Distillation
mi3 cubic miles
MOU Memorandum of Understanding
MPDES Montana Pollutant Discharge Elimination System
MVC Mechanical Vapor Compression
MVR Mechanical Vapor Recompression
NaCl Sodium Chloride
NAWI National Alliance for Water Innovation
ND North Dakota
ND DMRIC North Dakota Department of Mineral Resources Industrial Commission
NF Nanofiltration
NGOs Non-Governmental Organizations
NM EMNRD New Mexico Energy, Minerals, and Natural Resources Department
NM OCD Oil Conservation Division
NM OSE NM Office of State Engineer
NMAC New Mexico Administrative Code
NMED AQB NM ED Air Quality Bureau
NMED NM Environment Department
NMIMT New Mexico Institute of Mining and Technology
NMOCD New Mexico Oil Conservation Division
NMPWRC New Mexico Produced Water Research Consortium

NMTSO New Mexico Tech Seismological Observatory
NORM Normally Occurring Radioactive Material
NOW Non-Hazardous Oilfield Waste
NOx oxides of nitrogen
NPDES National Pollutant Discharge Elimination System
OCC Oklahoma Corporation Commission
OCC OGD OCC Oil and Gas Division
ODNR Ohio Department of Natural Resources
ODNR DOGRM Department of Oil and Gas Resources Management
ORP Oxidation-Reduction Potential
PADEP Pennsylvania Department of Environmental Protection
pCi/L picocurie per liter
pH potential of hydrogen
PM Project Manager
PRRC NMIMT Petroleum Research and Recovery Center
PTE Potential to Emit
PW produced water
PWMU Produced Water Management Unit
PWOF Produced Water Optimization Framework
QA Quality Assurance
QC Quality Control
R&D Research and Development
RCRA Resource Conservation and Recovery Act
RFI Request for Information
RFP Request for Proposal
RO Reverse Osmosis
RRC Texas Railroad Commission
RTS Radioactive Tracer Surveys
SAP Sampling and Analysis Plan
SCITS Stanford Center for Induced and Triggered Seismicity
SCOTUS Supreme Court of the United States
SDAS seismic action score
SDWA Safe Drinking Water Act
SMMP Seismic Monitoring and Mitigation Plans
SRA Seismic Response Areas
SRP Seismic Response Protocol
SWD Saltwater Disposal
SWRO Seawater Reverse Osmosis
TCEQ Texas Commission on Environmental Quality
TDS Total Dissolved Solids
TENORM Technologically Enhanced NORM
TOG Total Oil and Grease
TPDES Texas Pollutant Discharge Elimination System
tpy tons per year
TSS Total Suspended Solids
TVD true vertical depth
TXPWC Texas Produced Water Consortium
U.S. United States
UDOGM Utah Division of Oil, Gas, and Mining
UIC Underground Injection Control
USGS United States Geological Survey
VOC volatile organic compounds
WOGCCWyoming Oil and Gas Conservation Commission
WOTUS Water of the U.S.
WVDEP West Virginia Department of Environmental Protection

1 Produced Water Report – 2023 Update

1.1 Overview

The Ground Water Protection Council (GWPC) is a national group of groundwater protection and underground injection control state agencies. Since 1983, the Council's work has been an important focal point for oil and gas industry issues among state and federal governments, industry, environmental groups, and the scientific community. The Council exists for the "protection of groundwater resources for all beneficial uses," inclusive of produced water (PW) from oil and gas exploration and production.

Positioned at the intersection of energy and groundwater, GWPC's focus on the Safe Drinking Water Act (SDWA) at large and the Underground Injection Control (UIC) Program in particular coupled with a core mission to aid state regulatory programs makes GWPC a natural organization to help address PW as a resource. The GWPC also has historic relationships with several federal agencies, including the U.S. Environmental Protection Agency (EPA) and U.S. Department of Energy (DOE), as well as oil and gas advocacy groups and non-governmental organizations (NGOs), which orients the Council as a moderator of the ongoing conversation regarding the beneficial reuse of PW. The Council's June 2019 report entitled: "Produced Water Report: Regulations, Current Practices, and Research Needs" included contributions from numerous stakeholders regarding a sustainable future for PW management, including reuse. Though PW is already beneficially reused outside of the oil and gas industry, the Report noted that expanding external uses would be a vital factor contributing to the longevity of oil and gas exploration and production. The report also highlighted that additional dedicated research and technology development held the promise of making beneficial reuse safer.

Since its publication in 2019, the first GWPC Produced Water Report has been an important reference for industry stakeholders, and to retain that status, given the realized changes in the PW marketplace, periodic updating is necessary. With that in mind, those changes are highlighted in this 2023 Report, which updates the most significant regulatory, operational, and technological advancements relevant to PW, to present the current "state of the market" reference document for stakeholders.

1.2 Development Approach

The Produced Water Report - 2023 Update was developed using the most recent data and information available, focused on the most notable regulatory, technical, and operational changes that have happened in the PW management cycle for each region.

Data gathering and analyses focused on the critical aspects of the PW management cycle within each of the seven (7) most prominent oil and gas development regions (see **Figure 1**) in the Continental U.S.:

1. **Permian** (Including Midland and Delaware Basins) – TX, Southeast NM
2. **Eagle Ford** – TX (includes South Texas)
3. **Appalachian** (Including Utica and Marcellus Basins) – PA, OH, WV
4. **Bakken** – ND, MT
5. **Mid-Continent** – OK, Southern KS, North Texas
6. **Rocky Mountain**– CO/WY, UT, Northwest NM
7. **Haynesville** – AR/LA/Northeast TX

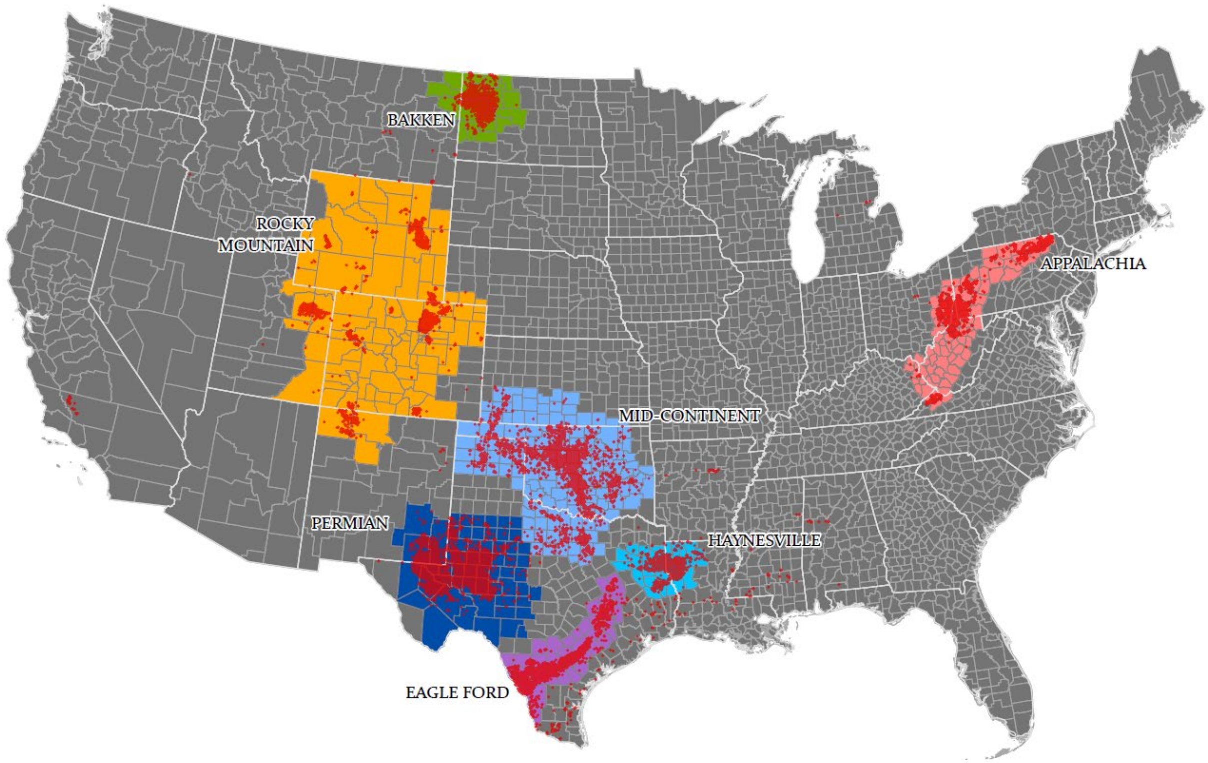

Figure 1: Seven Most Prominent Oil and Gas Development Regions in the Continental U.S.[1]

This 2023 Update retains the primary structure of the original report and is divided into 3 sections:

- **Legislative, and Regulatory Updates**: This section addresses the framework and regulatory changes impacting PW Management.
- **Notable Changes in Produced Water Operational and Management Practices:** The dynamic changes that have occurred in unconventional oil and gas operations regarding the PW management cycle, from the wellhead to final disposition are captured in this section.
- **Promising Produced Water Reuse Technologies and Associated Research Needs:** This section looks at the current PW reuse technologies with a Fit-For-Purpose approach for uses outside of oil and gas operations.

Notable changes that have occurred since the 2019 report were identified and prioritized by potential economic, environmental, and operational impacts within each section. To the extent possible, identified and anticipated changes in the Federal and State regulatory environments with the potential of impacting PW operational practices have been included. The technology and research needs within the PW marketplace have been identified and focus on technologies that better enable the reuse of PW outside of the oil and gas industry.

Currently, large volumes of PW are managed by various recycling methods such as enhanced oil recovery (EOR) and fracturing (completion) of new wells. For the purposes of this report, **"Recycling"** will refer to PW being reused within the oilfield, and **"Reuse"** will refer to all uses outside of oilfield

[1] ALL Consulting work product, Data source: FracFocus Chemical Disclosure Registry, Data Download SQL Data, analyzed accordingly based on well locations, August 2022.

operations, which is often referred to as "beneficial reuse." When PW cannot be economically recycled or reused, that water is typically disposed of in wells commonly referred to as SWD (Saltwater Disposal) wells, where it is no longer considered accessible. SWD are designated Class II wells under the SDWA. The use of injection wells is not applicable in many areas, and new approaches for handling PW have become necessary. Many states and stakeholders are recognizing PW as a resource, especially in water-scarce areas of the country, and asking what steps would be necessary to treat and reuse it for other purposes.

To illustrate the relative amount and importance of this vital and finite resource, **Figure 2** provides a visual comparison of the volumes of various water types globally.

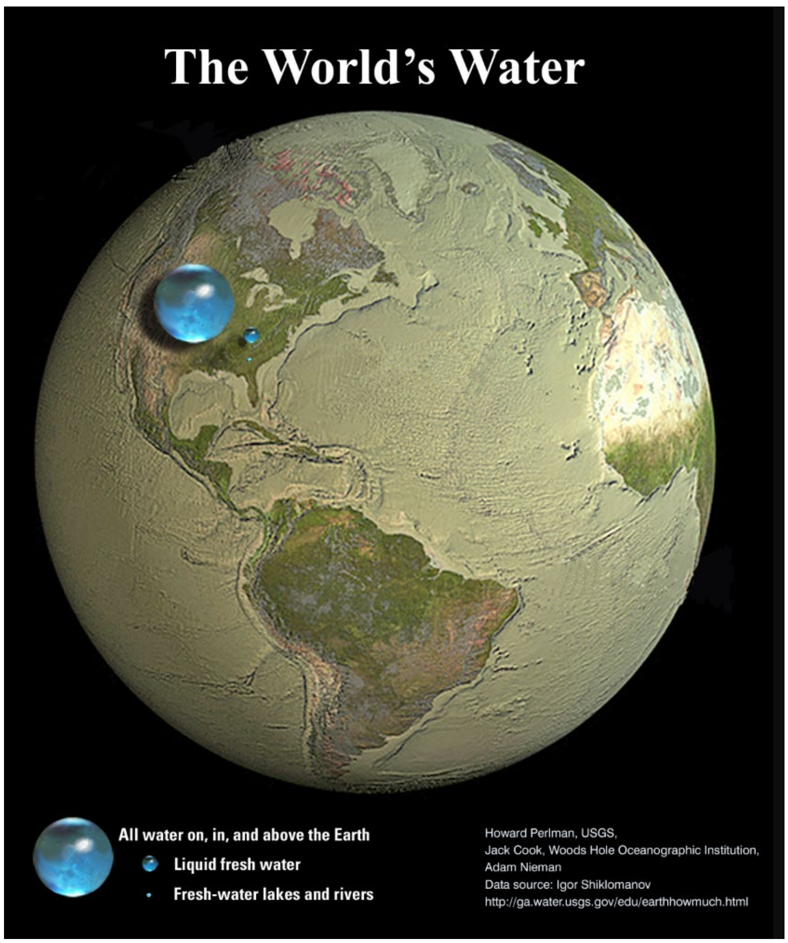

Figure 2: The World's Water: Big Picture of All Water vs. Fresh Water[2]

The image in **Figure 2** shows three blue spheres, representing the relative amounts of all of Earth's water, Earth's liquid fresh water, and water in lakes and rivers. The size of each sphere depicts in three dimensions the volume of water such that a visual comparison can be made with the volume of the globe. The largest sphere represents all of Earth's water and has a diameter of ~860 miles and a volume

[2] Howard Perlman, USGS, Jack Cook, Woods Hole Oceanographic Institution, Adam Nieman, Data source: Igor Shiklomanov Http://ga.water.usgs.gov/edu/earthhowmuch.html, All of Earth's Water in a single sphere!, July, 16, 2019, https://www.usgs.gov/media/images/all-earths-water-a-single-sphere

of ~332,500,000 cubic miles (mi^3) or 1,386,000,000 cubic kilometers (km^3). This sphere includes all of the water on the planet, in oceans, ice caps, lakes, rivers, groundwater, atmospheric water, and even the water in every person, plant, and animal.

The second largest blue sphere embodies the world's liquid fresh water and has a diameter of ~169.5 miles (272.8 kilometers) and a volume of ~2,551,100 mi^3 (10,633,450 km^3). The world's liquid fresh water includes groundwater, and water in lakes, swamps, and rivers. Approximately 99% is groundwater, much of which is not accessible to humans.

The third and tiniest bubble denotes the fresh water in lakes and rivers on the planet. The diameter of this sphere is ~34.9 miles (56.2 kilometers) and has a volume of only ~22,339 mi^3 (93,113 km^3). Most of the water people need every day comes from these surface-water sources.

The following graphic (**Figure 3**) shows the projected water stress in the U.S. by the year 2050, demonstrating the need and value for fresh water conservation across the U.S., the largest swath of concern encompasses the Permian and Eagle Ford development regions.

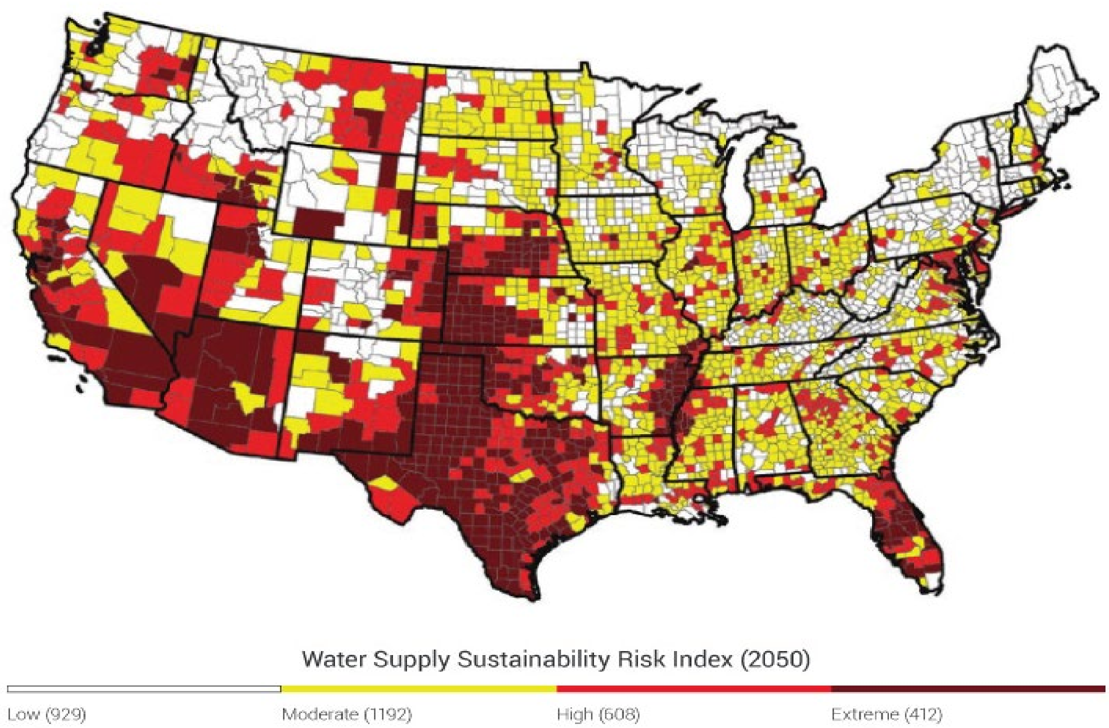

Figure 3: Projected Water Stress in the U.S. by Year 2050[3]

As shown in **Figure 3**, much of the extreme stress is centered in West Texas and the Permian Development Region, highlighting the potential value and the significance of beneficial reuse of PW in that area.

[3] National Climate Assessment, Interactive graphic – Climate Change Effects, Water Supply Sustainability Risk Index (2050) https://nca2014.globalchange.gov/highlights/report-findings/water-supply

Regarding the development and production of oil resources in the lower 48 states, **Figure 4** presents a comparison of the relative contribution to the domestic supply. Among the major producing regions, Texas leads the U.S. in oil production and with that accounts for the majority of PW volumes domestically.

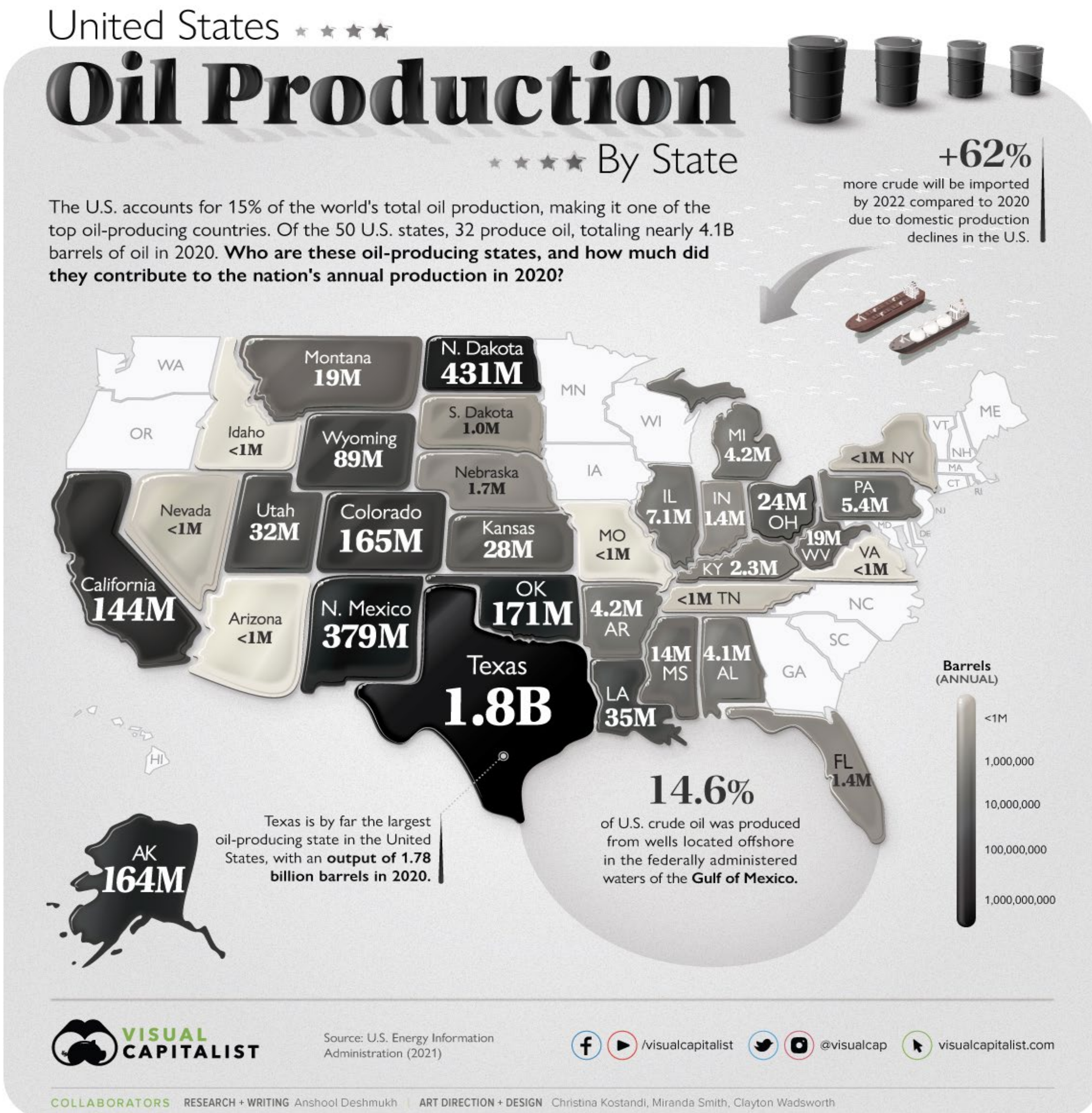

Figure 4: U.S. Oil Production by State for 2020[4]

To further confirm the relevancy of the graph above, the Permian Development Region consistently produces more than 50% of all oil produced in the United States, followed closely by the Bakken, and then the Eagle Ford, see **Figure 5.**

[4] Anshool Deshmukh, 2021, Mapped: Visualizing U.S. Oil Production by State, Visual Capitalist, August 10, 2021, Art – C. Kostandi, M. Smith, C. Wadsworth, Data Source: U.S. EIA 2021, https://www.visualcapitalist.com/mapped-u-s-oil-production-by-state/, obtained August 2022.

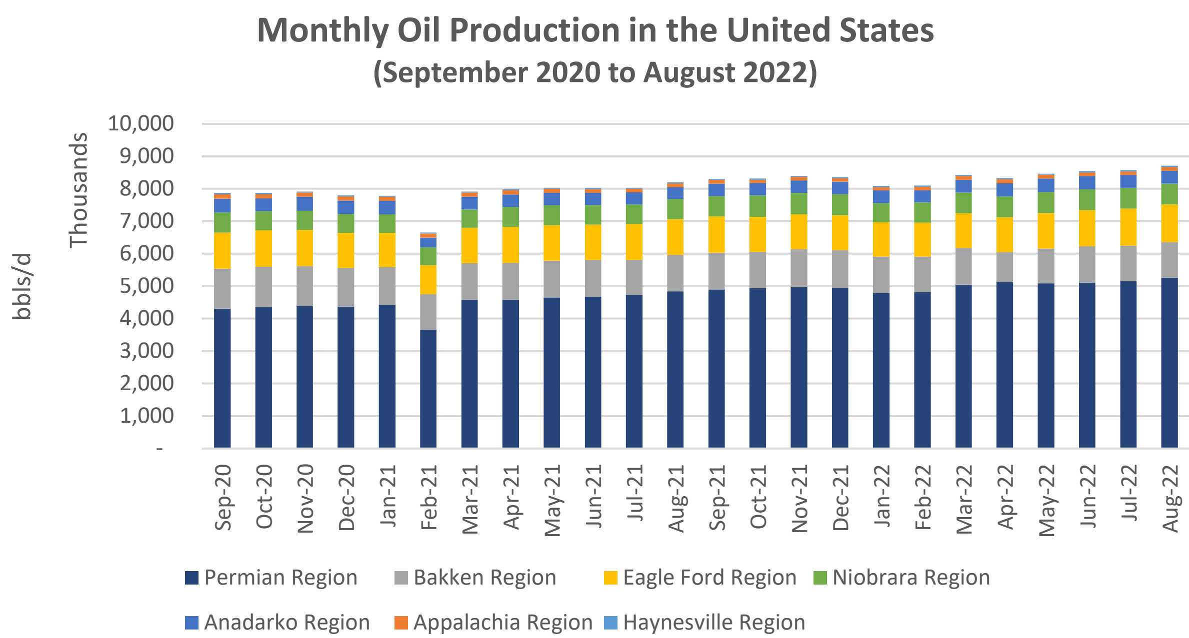

Figure 5: U.S. Monthly Oil Production (September 2020 to August 2022)[5]

Along with more than 50% of the oil in the U.S. being produced in the Permian Development Region, an overwhelming majority of the PW is also generated within the region. The graph in **Figure 6** puts the volume of PW generated by the Permian Development Region into context when compared to other regions. For example, in 2021, the Permian generated 49 times more PW than the Appalachian Development Region, and it is projected that by 2030, the Permian will produce 69 times more PW than the Appalachian.

The graph in **Figure 7** shows that natural gas production in the Appalachian Development Region produces significantly more gas than any other region, often exceeding 1/3 of the total production across the U.S., reflecting an inverse proportion when aligned with PW volumes.

The graphic in **Figure 8** indicates, the overall number of wells completed across all seven regions, and shows that new drilling activity has trended lower since 2014. However, the total base water volume used per completion has increased as can be seen in **Figure 9**. This increase in total base water volume per well seems to be related to the drilling of longer laterals, thus requiring larger volumes of water for stimulation practices.

These different findings and their juxtaposition demonstrate the importance of data gathering and analysis to understand the challenges in PW management under varying regional conditions and help migrate the successful approaches from one basin to another.

[5] ALL Consulting work product, Data source U.S. EIA, retrieved September 2022 from Petroleum & Other Liquids, Crude Oil Production, Monthly-Thousand Barrels, MSExcel Download Series History
https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_m.htm

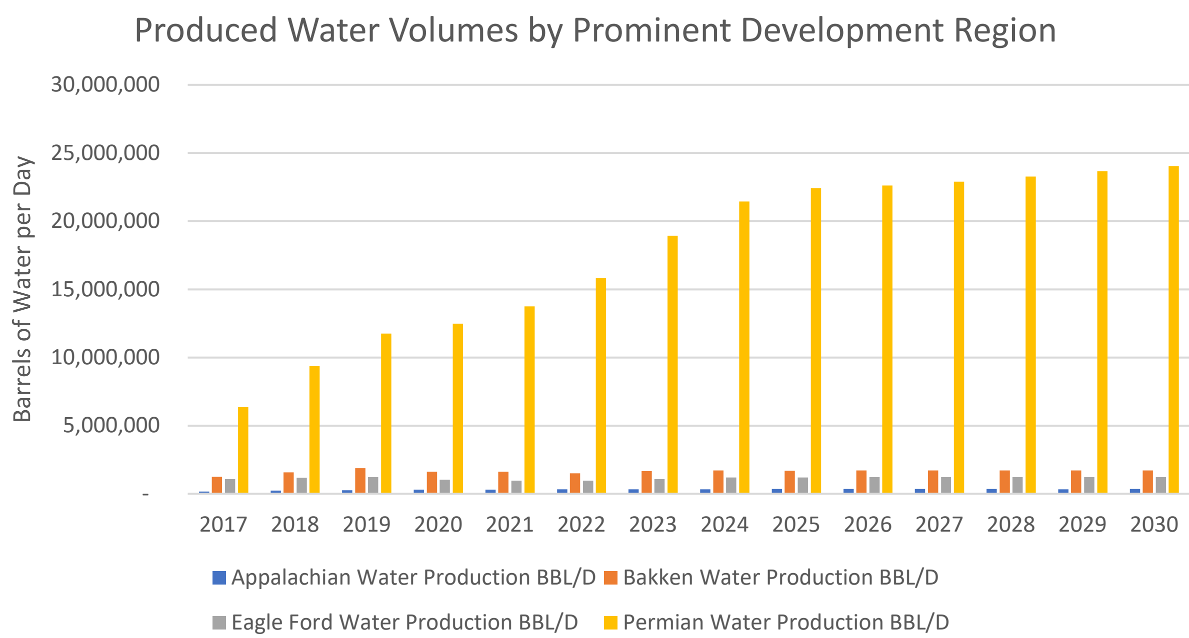

Figure 6: Produced Water Volume by Prominent Development Region[6]

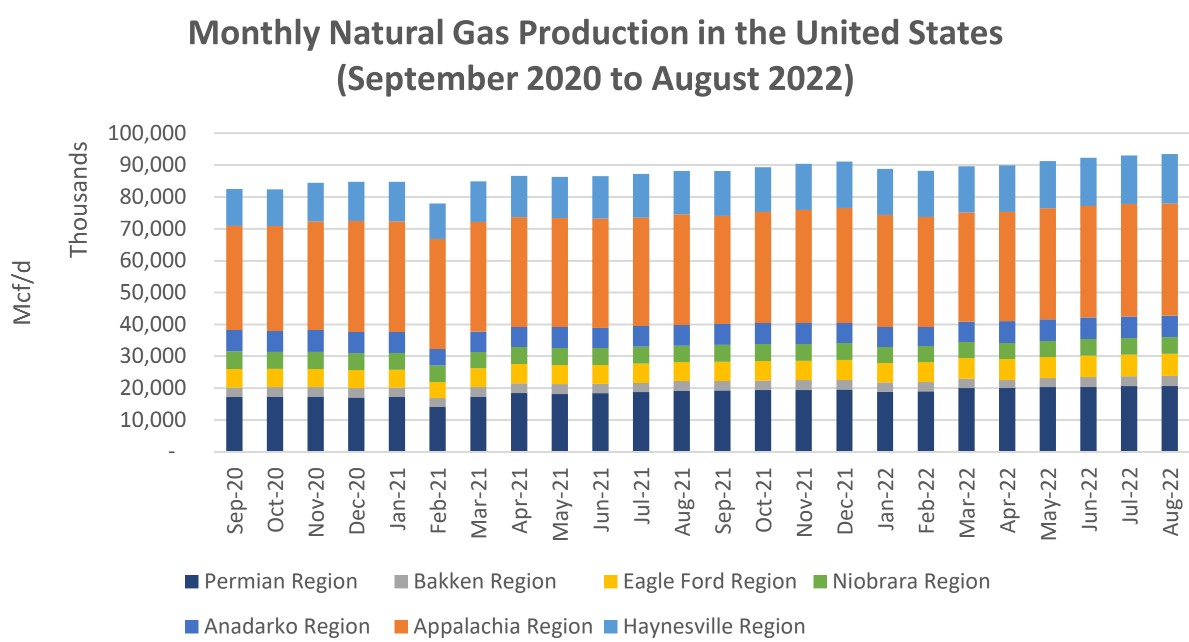

Figure 7: U.S. Monthly Natural Gas Production (September 2020 to August 2022)[7]

[6] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

[7] ALL Consulting work product, Data source U.S. EIA, retrieved September 2022 from Natural Gas, Natural Gas Gross Withdrawals and Production, Monthly-Million Cubic Feet, MSExcel Download Series History, https://www.eia.gov/dnav/ng/ng_prod_sum_a_EPG0_FGW_mmcf_m.htm

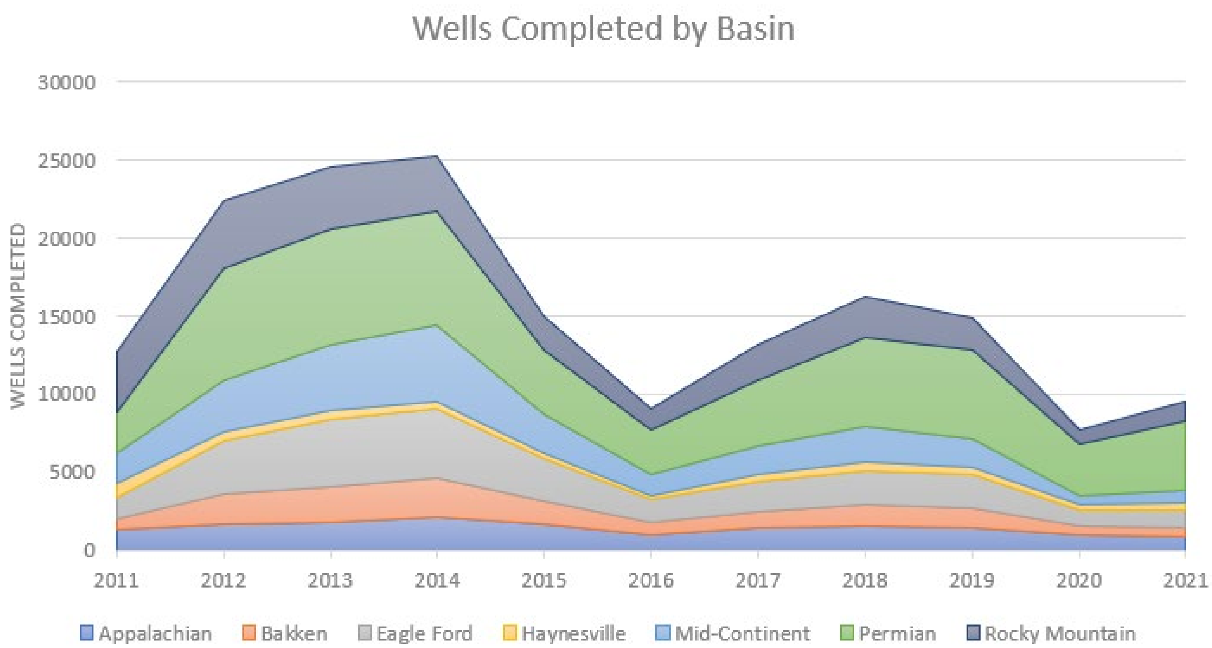

Figure 8: Wells Completed by Basin (2011 – 2021)[8]

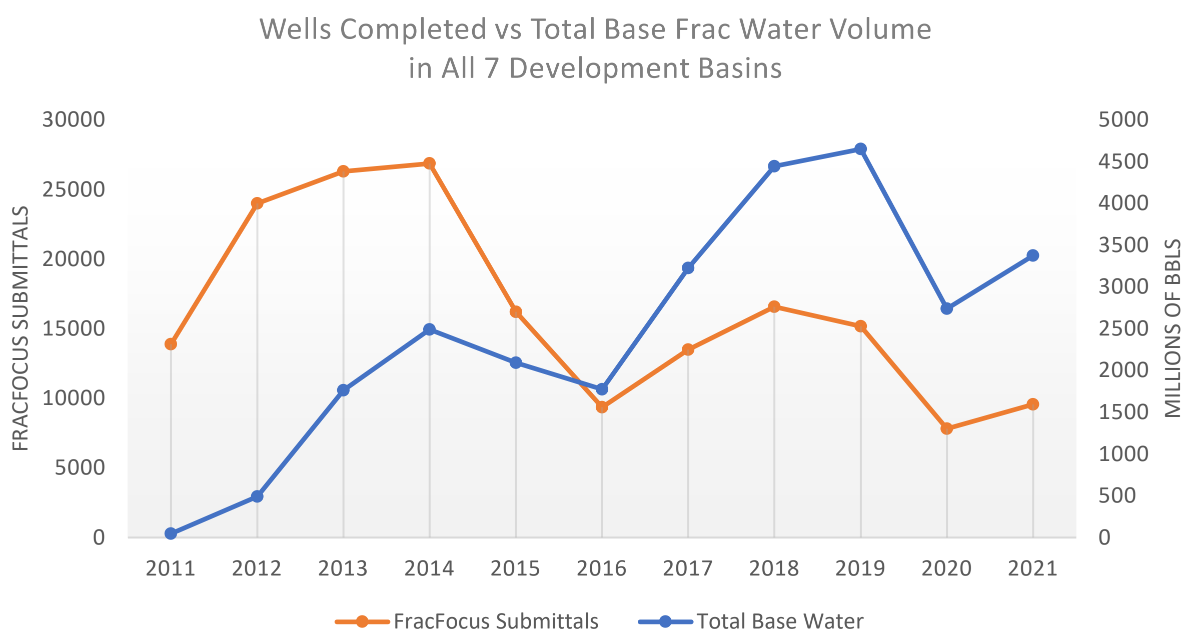

Figure 9: Wells Completed vs. Total Base Frac Water Volume (2011 – 2021)[9]

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[8] ALL Consulting work product, Data source: FracFocus Chemical Disclosure Registry, Data Download SQL Data, analyzed accordingly, June 2022.

[9] ALL Consulting work product, Data source: FracFocus Chemical Disclosure Registry, Data Download SQL Data, analyzed accordingly, July 2022.

Availability of Produced Water Data – Focus on Top Four (4) Regions

Due to the availability and integrity of reported data from public resources, the acquisition and development of this data were focused on the following four development regions: Permian, Eagle Ford, Bakken, and Appalachian. Over time, it is envisioned that the same level of data and analysis will be made available for every development region. However, as these four regions currently have the greatest amount of information available and combined with the fact that these four regions comprise the largest amount of hydrocarbon production in the U.S., this report has showcased and analyzed the data from these regions.

Water Midstream Sector – Growth Explosion

When the original GWPC PW Report was issued in 2019, the forecasted explosion of 3rd party midstream companies entering the marketplace had already begun. One year later (February 2020) an estimated $9-11 billion of private capital was committed to the oilfield water midstream business, with an estimated additional $16 billion of private investment expected to be placed into this sector.[10] Due to the confidential nature of private fund placement into these emerging market companies, the amount of overall investment made into midstream companies and operations may well be significantly greater than these estimates. The reach of this midstream market investment and development had a significant impact across the entire U.S. marketplace, predominantly in the Permian Development Region.

Permian – Focal Point for Produced Water Management

Since 2019, the Permian Development Region has emerged to expand virtually every regulatory and operational challenge associated with the management of large volumes of high salinity PW. The confluence of high levels of oil production activity and corresponding PW volumes within this landlocked area projected high levels of water scarcity, and growing constraints on disposal, making the Permian the undisputed focal point for PW management in the U.S.

Due to the ongoing development activity and recognizing the need to support all stakeholders in the Permian, both Texas and New Mexico have created PW consortiums to drive changes in the necessary research, regulatory, and operational best practices for their respective states. By comparison to this region, the changes in the PW management environment of the other six development regions have been mostly stagnant, with little to no notable changes. As a result of this glaring set of market dynamics, this Produced Water Report – 2023 Update intentionally focuses on the Permian as it encompasses the most notable changes since the original report, but is currently leading all aspects of PW regulatory, operational, and research activities which will predictably impact the other regions in the foreseeable future.

[10] The Future of Water Midstream, Emerging Opportunities for Water Players in the Permian Basin, Market Report Overview, The Future of the Water Midstream, February 7, 2020, Global Water Intelligence, https://www.globalwaterintel.com/products-and-services/market-research-reports/the-future-of-water-midstream August 2022

2 Legislative and Regulatory Updates

This section focuses on notable updates to federal and state legislation and regulatory changes. The federal section addresses updates to the Clean Water Act (CWA) and National Pollution Discharge Elimination System (NPDES), the SDWA, the Resource Conservation and Recovery Act (RCRA), the EPA Water Reuse Action Plan, and the United States Geological Survey (USGS) Oil and Gas Project. The state section provides updates for 14 states via individual subsections. Finally, since the original report, there has been an increase in induced seismicity events, and therefore a third section has been devoted to this topic and its most notable impacts.

2.1 Federal Legislative and Regulatory Changes

2.1.1 Clean Water Act and NPDES Discharge

The EPA conducted a study entitled *Oil and Gas Extraction Wastewater Management Under the Clean Water Act*, that was released in 2019.[11] The Agency is still determining what, if any, next steps should be taken regarding PW management under the CWA. However, EPA has approved Texas' request for NPDES program authorization for discharges from PW and other oil and gas discharges. The Texas Commission on Environmental Quality (TCEQ) now has partial primacy over the NPDES program for PW.

In April 2020, the Supreme Court of the United States (SCOTUS) made a decision in the County of Maui, Hawaii v. Hawaii Wildlife Fund case requiring pollution discharged from a point source or its functional equivalent that flows to jurisdictional Waters of the United States (WOTUS) to be regulated by permit, even if that discharge is into groundwater first. Specifically, the Court found that the CWA requires a permit if there is a functional equivalent of a direct discharge from a point source into navigable waters. This is an important interpretation because the County injects treated wastewater ("effluent") that meets R-1 water standards, Hawaii's highest standards for recycled water, into UIC wells. Once injected, the effluent rapidly mixes with groundwater and diffuses vertically and horizontally, eventually migrating to the ocean. Hence, the SCOTUS is stating the County indirectly discharged a pollutant (e.g., it's treated effluent) into the ocean through a groundwater conduit via a UIC well and is recognizing the groundwater as a "point source" as defined by the CWA, and simultaneously as a "navigable water" under the CWA.[12] The ramifications of this decision are perplexing but the EPA will work with state permitting agencies and the regulatory community to provide site-specific, science-based evaluations grounded in the CWA permitting requirements. Noteworthy is the Biden administration has rescinded the Trump administration's published guidance.

2.1.2 SDWA – UIC / Aquifer Exemption

EPA published an interactive map that allows users to view aquifers that have been approved for exemption by EPA under the SDWA. The most recent update came in July 2021 and is accessible at the following location:

https://epa.maps.arcgis.com/apps/MapSeries/index.html?appid=426ef9d346f9487e96ee5899ab67a2e4

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[11] U.S. EPA, May 2020, Summary of Input on Oil and Gas Extraction Wastewater Management Practices Under the Clean Water Act, EPA- 821-S19-001 https://www.epa.gov/sites/default/files/2020-05/documents/oil-gas-final-report-2020.pdf

[12] County of Maui, Hawaii v. Hawaii Wildlife Fund, accessed December 14, 2023, at https://www.oyez.org/cases/2019/18-260

2.1.3 RCRA Subtitle D

On May 4, 2016, the Environmental Integrity Project, together with six other parties, filed a lawsuit that alleged EPA had failed to perform non-discretionary duties under RCRA, specifically regarding:[13]

- Review and revision of Subtitle D criteria for oil and gas wastes (40 CFR Part 257).
- Review and revision (if necessary) of state plan guidelines for oil and gas wastes (40 CFR Part 256).

EPA entered into a consent decree establishing whether it was warranted to revise the current rules regarding E&P oil and gas wastes with a deadline of March 15, 2019. In April 2019, EPA determined that regulatory revisions regarding the management and disposal of E&P wastes are unwarranted.

2.1.4 EPA Water Reuse Action Plan

The EPA Water Reuse Action Plan was established in partnership with over 100 stakeholders in the water sector. The plan's actions are designed to propel headway on the reuse of our nation's water resources with regard to the improvement of security, sustainability, and resilience with the impeding changes in climate. A link to the EPA site is as flows:

- https://www.epa.gov/waterreuse/national-water-reuse-action-plan-online-platform

Potentially applicable actions within the plan include:

- 3.1 Compile Existing Fit-for-Purpose Specifications
- 3.8 Assess Regulatory Programs for Produced Water Reuse

In April 2022, a document from the Environmental Defense Fund (EDF) was prepared in support of this action and it can be found at the following link;

- https://www.ecos.org/wp-content/uploads/2022/04/EDF-Assessment-of-Produced-Water-Land-Application.pdf

2.1.5 USGS: Oil and Gas Waters Project:

The primary objective of this project is to provide information on the volume, quality, impacts, and possible uses of water produced during the generation and development of energy resources (particularly hydrocarbons), as well as related fluids injected into reservoirs for energy development and associated waste disposal. The project link is as follows:

- https://www.usgs.gov/centers/geology-energy-and-minerals-science-center/science/oil-and-gas-waters-project

The project tasks and contacts are provided in the following bullets:

- Characterization and Reuse of Oil and Gas Waters
  Madalyn Blondes, Research Geologist, Geology, Energy & Minerals Science Center,
  Email: mblondes@usgs.gov, Phone: 703-648-6509

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[13] Management of Exploration, Development and Production Wastes: Factors Informing a Decision on the Need for Regulatory Action, April 2019 accessed at https://www.epa.gov/sites/default/files/2019-04/documents/management_of_exploration_development_and_production_wastes_4-23-19.pdf

- Quantities of Water Associated with Oil and Gas, and Quantifying Broader Impacts of Oil and Gas Developments
  Seth Haines, Research Geophysicist, Central Energy Resources, Science Center,
  Email: shaines@usgs.gov, Phone: 303-236-5709
- Brine Research Instrumentation and Experimental (BRInE) Lab
  Aaron Jubb, Research Chemist, Geology, Energy & Minerals Science Center,
  Email: ajubb@usgs.gov, Phone: 703-648-6481
- Geophysical Mapping of Produced Water in Near-Surface Environments
  Lyndsay B Ball, Research Geophysicist, Geology, Geophysics, and Geochemistry Science Center,
  Email: lbball@usgs.gov, Phone: 303-236-0133
- Big Data and Data Visualization
  Jenna L Shelton, Ph.D., Associate Program Coordinator, U.S. GeoFramework Initiative & STATEMAP, National Cooperative Geologic Mapping Program,
  Email: jlshelton@usgs.gov, Phone: 571-512-1641

2.1.6 Other Potential Helpful Links

- IOGCC PW ownership survey at https://iogcc.ok.gov/produced-water-ownership-survey
- There is a CWA Hazardous substances proposal that potentially has implications to operations should it be determined that PW itself is applicable (that is still somewhat an open question under the significant harm criteria proposed in the proposal). More info on this proposal:
  - https://www.epa.gov/hazardous-substance-spills-planning-regulations
- The CLEAN Future Act and Oilfield Produced Water Regulation: Potential Consequences for the U.S. and Global Energy Transition
  - Identifies consequences of EPA potentially classifying prod. water as a hazardous waste.
  - https://www.bakerinstitute.org/files/17421/
- EPA May Allow Disposal of Oil Waste in Waterways. Is the Public at Risk?
  - Discusses the possibility of treated PW discharge into water ways.
  - https://oklahomawatch.org/2019/12/02/epa-may-allow-disposal-of-oil-waste-in-waterways-is-public-at-risk/

2.2 Legislative and Regulatory Changes by State

Since the original report, there have been many legislative and regulatory changes that have impacted the management, treatment, and disposition of PW which have taken place on a state-by-state basis. Notable changes and the accompanying state agency that implements and enforces the corresponding regulations have been identified and listed in the following subsections. For brevity and conservation of space, this information has been provided in a bullet format with pertinent items identified.

2.2.1 Arkansas

The agencies that oversee the implementation of regulations pertaining to PW in Arkansas are the Arkansas Department of Energy and Environment – ADEE and the Arkansas Oil & Gas Commission –

AOGC. No new rules or regulatory changes have been adopted relating to PW since the original GWPC Produced Water Report was issued.

2.2.2 Colorado

The Colorado Oil & Gas Conservation Commission (COGCC) is the agency responsible for ensuring PW is management appropriately in Colorado.

- Produced Water Quality Model Sampling and Analysis Plan (SAP) was established in April 2022,
    - Establishment of "Best Practice Protocols"
    - For parties who engage in sampling and analysis activities pursuant to Rules 909.j, 803.g(5)C, 803.g(5)D, 806.a, 806.b, 806.c, 809, 810, and 811
    - https://cogcc.state.co.us/documents/sb19181/Guidance/Mission_Change_Guidance/PW%20COGCC_Model_SAP_V1%2023Feb2022_Final.pdf
- Sampling and Analysis of Naturally Occurring Radioactive Material in Oil and Gas Produced Water (CO)
    - Special Project 10243 was undertaken to better understand the activities of NORM in PW
    - https://cogcc.state.co.us/documents/library/Technical/Public_Health_Safety_and_Welfare/Water%20Sources%20and%20Demands%20for%20Hydraulic%20Fracturing%20of%20Oil%20and%20Gas%20Wells%20in%20Colorado.pdf
- Water Sources and Demands for Hydraulic Fracturing of Oil and Gas Wells in Colorado (CO)
    - Examines recent (2021) water demands for hydraulic fracturing in CO; includes a brief discussion of produced/recycled/reused water.
    - https://cogcc.state.co.us/documents/library/Technical/Public_Health_Safety_and_Welfare/Water%20Sources%20and%20Demands%20for%20Hydraulic%20Fracturing%20of%20Oil%20and%20Gas%20Wells%20in%20Colorado.pdf
- Aquifer Exemption Evaluation (07/24/2020)

2.2.3 Kansas

The Kansas Corporation Commission (KCC) has not adopted any notable changes in the regulatory or legislative frameworks, except for those developed to address induced seismicity, which were covered in the earlier section, since the original GWPC Produced Water Report was issued in 2019.

2.2.4 Louisiana

The Louisana Department of Natural Resources (LADNR) has adopted major regulatory changes regarding PW, called the "Produced Water Injection Incentive (2018)." A summary of this revised Statute (Title 47) RS 47:633.5, Produced Water Injection Incentive, is provided below.

- The Louisiana Department of Environmental Quality (DEQ), Office of Water Resources, was directed to act in conjunction with the Louisiana Department of Natural Resources (DNR) to conduct a risk analysis of the discharge of PWs from oil and gas activities onto the ground and into the surface waters, and to examine the environmental risks and the economic impact on the oil and gas industry if the discharge was to be prohibited.
- Details were not provided, but the risk analysis was reported as not being properly conducted as directed. However, PW into Louisiana's surface waters was prohibited by rules promulgated in Louisiana (1991), as administered by the DEQ.

- To help accomplish the objective of reducing the discharge of PW, and to lessen the financial burden on the oil & gas industry, the Produced Water Injection Incentive was promulgated in 2018 to provide operators severance tax savings if they inject PW into an oil and gas reservoir, from the same reservoir and field.
- The severance tax is reduced on oil and gas sales when PW is injected into an oil reservoir.
    - For oil, when PW is injected into an oil reservoir for the purpose of increasing recovery, the severance tax on one bbl of oil incrementally produced is reduced by 20% of the tax that otherwise would be due.
    - For gas, when PW is injected into a gas reservoir for the purpose of increasing recovery, the severance tax on one Mcf of gas incrementally produced is reduced by 20% of the tax that otherwise would be due.

2.2.5 Montana

The Montana Board of Oil and Gas Conservation (MBOGC) has made some changes regarding PW discharges under the Montana Pollution Discharge Elimination System (MPDES), a summary is provided below:

- Montana Pollutant Discharge Elimination System (MPDES) Fact Sheet for Produced Water General Permit (MT)
    - General Permit authorizes the disposal of PW into ephemeral drainages and impoundments constructed in ephemeral drainages for beneficial uses only.
    - https://deq.mt.gov/files/Water/WQInfo/Documents/2020%20Public%20Notices/MT-20-14_MTG31000/2020_FS_MTG310000.pdf

2.2.6 New Mexico

The New Mexico Energy Minerals and Natural Resources Department (NM EMNRD) and Oil Conservation Division (NM OCD) have seen considerable changes to their regulations governing the management of PW.

- Produced Water Regulating Bodies:
    - The authority to regulate PW in New Mexico has been granted to the following organizations through the New Mexico Statues 1978 Chapter 70, including articles 2 (Oil Conservation Commission; Division; Regulation of Wells), 12 (Surface Owner Protection Act), and 13 (Produced Waters):
        - New Mexico Natural Resources Division – Oil Conservation Division: Regulated the disposal and reuse of Produced Water within the oil and gas industry.
        - New Mexico Environmental Department – Water Quality Control Commission: Regulates the use of Produced Water outside of the oil and gas industry under the PW act and the Water Quality Act.
        - New Mexico Office of the State Engineer: Regulates the re-use of PW outside of the Oil & Gas industry in conjunction with existing permitted water rights.
- Produced Water Regulations:
    - 2019 New Mexico Produced Water Act
        - In 2019 the New Mexico State Legislature passed the New Mexico Produced Water Act.

- Through this Act, the statutory and regulatory authority for the reuse of PW was modified:
  - ✓ Reuse inside the oil and gas sector remains under the NM Oil Conservation Division (OCD) of the NM EMNRD,
  - ✓ Reuse outside the oil and gas sector was designated to the NM Environment Department (NMED).
- The act gave the NMED the responsibility to develop regulations and policies to govern the reuse of PW outside the oil and gas sector in order to:
  - ✓ enhance fresh water supplies and fresh water sustainability,
  - ✓ reduce and eliminate the use of fresh water in the oil and gas sector,
  - ✓ support new economic development,
  - ✓ improve ecological habitat recovery and diversity, all while maintaining public and environmental health and safety.
- To help establish and conduct Research and Development (R&D) efforts needed to accomplish the above goals, the NMED initiated a Memorandum of Understanding (MOU) with New Mexico State University to create the New Mexico Produced Water Research Consortium (NMPWRC).
- The NMPWRC was chartered to lead a collaborative technical forum of government, industry, and academia, to identify and establish a research and development program to identify and address existing science and technology challenges associated with the treatment and reuse of PW for specific fit-for-purpose uses outside the oil and gas sector.
  - ✓ The NMPWRC was also tasked to support NMED in developing science-based regulations and policies to facilitate treated PW reuse that would be protective of public, environmental, and ecological health, and safety.
  - ✓ To accomplish these objectives, the NMPWRC developed an operational framework and structure to support a broad science and technology research, development, and testing program to address the technical, cost, and ecological risks of the fit-for-purpose reuse of treated PW outside the oil and gas industry.

o In response to the Produced Water act passed (HB 546) in 2019 the following changes were made within the PW governing bodies in NM:
- NMOCD revised NMAC Title 19 Chapter 15 parts 2, 15, 34 through division order R-21343-A to better align with the Produced Water Act. Some notable revisions are listed below:
  - ✓ Updated the definition of PW to match the PW act.
  - ✓ Requiring operators to complete a monthly Water Use Report that outlines the volume and quality of water used (PW, water > 10,000 TDS (other than PW), <10,000 TDS, water < 1,000 TDS).
  - ✓ Updating the scope and authority statement in NMAC 19.15.34.
  - ✓ Clearly outlining the requirements for reuse, recycling, or disposal of PW in NMAC 19.15.34.8.
- NMED is addressing the Produced Water Act in two phases:
  - ✓ First, by implementing near-term narrow rulemaking prohibiting Untreated PW from being used outside of the oil and gas industry.

        - ✓ Second, by partnering with New Mexico State University for the Produced Water research consortium to develop scientifically based rules for the discharge handling, transportation, storage, and recycling/reuse of PW outside of the oil field.

- NMAC 20.2.50: NMED's Newly Released Oil and Gas Sector Ozone Precursor Rule Impose Stringent Standards to Significantly Reduce Emissions from Produced Water Operations
    - ▪ On July 20, 2022, The New Mexico Environment Department (NMED) announced the release of the final version of the New Mexico Administrative Code (NMAC) 20.2.50 for Ozone Precursor Pollutants for the Oil and Gas Sector.
    - ▪ The objective of this rule was to Establish emission standards for volatile organic compounds (VOC) and oxides of nitrogen (NOx) for oil and gas production, processing, compression, and transmission sources.
    - ▪ NMAC 20.2.50 became effective on August 5, 2022, and applies to crude oil and natural gas production and processing equipment. Oil transmission pipelines, oil refineries, natural gas transmission pipelines (except transmission compressor stations), and saltwater disposal facilities are not subject to this part.
    - ▪ The following Counties of the state are currently subject to this Part:
        - ✓ Chaves
        - ✓ Dona Ana
        - ✓ Eddy
        - ✓ Lea
        - ✓ Rio Arriba
        - ✓ Sandoval
        - ✓ San Juan
        - ✓ Valencia
    - o 20.2.50.123 Storage Vessels – Applicability
        - ▪ New storage vessels with a Potential to Emit (PTE) equal to or greater than two (2) tpy of VOC
        - ▪ Existing storage vessels with a PTE equal to or greater than three (3) tpy of VOC in multi-tank batteries
        - ▪ Existing storage vessels with a PTE equal to or greater than four (4) tpy of VOC in single-tank batteries
    - o 20.2.50.123 Storage Vessels - Emissions Standards
        - ▪ Combined Capture and Control of VOC Emissions
        - ▪ Existing storage vessels will be phased in according to the following schedule:
            - ✓ 30% of a Company's existing storage vessels controlled by January 1, 2025.
            - ✓ At least an additional 35% of a Company's existing storage vessels controlled by January 1, 2027.
            - ✓ The remaining existing storage vessels controlled by January 1, 2029.
        - ▪ New storage vessels must meet requirements upon startup.
    - o 20.2.50.123 Storage Vessels - Monitoring requirements:
        - ▪ Monthly monitor, calculate or estimate total monthly liquid throughput and the upstream separator pressure.

- Conduct an AVO inspection on a weekly basis.
- Inspect storage vessel monthly to ensure compliance with 20.2.50.123.
- Date and time stamp the monitoring event.
- Comply with 20.2.50.115 for control devices.

- 20.2.50.126 Produced Water Management Units
  - Definition: "Produced Water Management Unit" (PWMU) means a recycling facility or a permanent pit or pond that is a natural topographical depression, man-made excavation, or diked area formed primarily of earthen materials (although it may be lined with man-made materials), which is designed to accumulate PW and has a design storage capacity equal to or greater than 50,000 barrels.
  - Applicability: As defined, PWMUs and their associated storage vessels.
  - Emission Standards:
    - ✓ Owner/operator shall use good operational or engineering practices to minimize emissions of VOC from PWMU and their associated storage vessels.
    - ✓ Owner/operator shall not allow any transfer of untreated PW to a PWMU without first treating the PW in a separator and/or storage vessel to minimize entrained hydrocarbons.
    - ✓ Existing Facilities must comply within 2 years of the effective date of this Part.
    - ✓ New Facilities must comply upon startup.
    - ✓ Control such storage vessels in accordance with the requirements of Section 123.
    - ✓ Or submit a VOC minimization plan to the department demonstrating that controlling VOC emissions from storage vessels associated with the PWMU is technically infeasible without supplemental fuel.
  - Monitoring Requirements
    - ✓ Develop a protocol to calculate the VOC Emissions from each PWMU including throughput monitoring, semi-annual sampling and analysis of the liquid composition, hydrocarbon measurement method, sample size, and sample chain of custody requirements.
    - ✓ Calculate the monthly total VOC emissions in tons from each unit with the first month of emissions calculation commencing within 180 days of the effective date of this Part (August 5).
    - ✓ Monitor monthly, the best management and good operational or engineering practices implemented to reduce emissions at each unit to ensure and demonstrate their effectiveness.
    - ✓ Upon request by the department (NMED AQB), sample the PWMU to determine the VOC content of liquid.

2.2.6.1 NMOCD Policy and Procedural changes:

While not codified within the New Mexico Administrative Code, the oil conservation division has put in place policies and procedures surrounding SWDs to further protect the environment from negative effects associated with the injection and storage of PW. These policies and procedures can be found in guidance documents, public notices, and through communication with the division. Some of these policies and procedures are outlined in the following bullets:

- For Deep Disposal wells in the Delaware Basin NMOCD outlined the following practices for deep (injection into formation below the Woodford shale):
  - Increased the notification set back from ½-mile to 1 mile.
  - Increased the area of review from ½-mile to 1 mile.
  - Included the requirement for a seismicity Risk Assessment.
  - Included as a permit condition that operators determine the static reservoir pressure before commencing injection operations.
  - Placed a 1.5-mile offset requirement from any other deep SWDs.

2.2.6.2 Other New Mexico References

The links below discuss the initial changes to the New Mexico Administrative Code to comply with the PW act. While unable to find any articles stating any newly proposed rule changes to continue to refine PW use, it is clear that NMOCD, NMED, and the Office of State Engineer (OSE) are working with the PW consortium to continue to study PW uses with the intent to implement rules once the appropriate amount of research has been conducted.

- NMOCD Statistics Page
  - Contains reports listing out the PW volumes by district or operator 2014- current.
  - https://www.emnrd.nm.gov/ocd/ocd-data/statistics/
- Application Permits Notification – “How To” Guides
  - Provides an overview of the application and forms needed for recycling facilities and discharge permits, and provides notices for those seeking discharge permit applications.
  - https://www.emnrd.nm.gov/ocd/permitting-resources-how-tos/
- Current Rules
  - Provides a link to NMOCD rules, including those rules pertaining to PW.
  - https://www.emnrd.nm.gov/ocd/occ-info/og-rules-and-forms/
- Produced Water Research Consortium Formed in NM
  - Outlines some of the powers provided through the "PW act" and indicates that regulations pertaining to the use of treated PW outside of the oil & gas industry will be coming in the near future.
- Produced Water Public Meeting presentation *(2019 post PW act)
  - Attention: Slide 25
- NMOCD order R-21343 amending NMOCD rules 19.15.2, 19.15.16, and 19.15.34 to align with the PW act.
  - https://ocdimage.emnrd.nm.gov/imaging/HearingOrderFileView.aspx?OrderNo=R-21343-A
- Article outlining rule adoptions made to address PW act. (Order No. R-21343-A)
  - https://www.modrall.com/2020/12/07/new-mexico-oil-conservation-commission-adopts-rule-changes-concerning-produced-water/
- NMED presentation over their responsibilities under the PW act.
  - https://www.nmlegis.gov/handouts/WNR%20090320%20Item%204%20NMED%20Produced%20Water%20Act%20Implementation%20Update.pdf

2.2.7 North Dakota

The North Dakota Department of Mineral Resources Industrial Commission (DMRIC) is responsible for overseeing the administration of PW with the state.

- Saltwater Disposal into Potentially Productive Formations (2019)
  - Outlines the process for injection well applications into potentially productive formations.
  - https://www.dmr.nd.gov/dmr/sites/www/files/documents/Oil%20and%20Gas/RulesRegsPolicies/Saltwater_Disposal_into_Potentially_Productive_Formation.pdf
- Final Report on Produced Water Management and Recycling Options in North Dakota (2020)
  - Discusses multiple aspects (regulatory, scientific, technological) of PW management in ND. Covers trends and future possibilities, including re-use.
  - https://www.ndlegis.gov/files/committees/66-2019/21_5181_03000appendixb.pdf
- Oilfield Brine Use in Dust or Ice Control
  - Outlines approval process for use of brine source as dust and/or ice control as a substitute for commercial product
  - https://deq.nd.gov/Publications/WQ/5_SP/OilFieldBrine_20191210_Final.pdf
- Produced Water Overview
  - Overview of Class II UIC program (ND) as of 2019
  - https://www.r8pa.com/Presentations/2019/Produced_Water_Presentation_IPP_Conf_2019.pdf
- Completion Design Evolution for Saltwater Disposal Injection Wells in the Bakken Play
  - Discusses ideal reservoir characteristics for new disposals in Williston Basin and Bakken Play. (Pay wall $$)
  - https://onepetro.org/URTECONF/proceedings-abstract/21URTC/3-21URTC/D031S075R003/465393
- Water Pressures
  - Discusses options for PW re-use in Bakken (Geologic Homogenization Conditioning and Reuse (GHCR) Project)
  - https://jpt.spe.org/water-pressures

2.2.8 Ohio

The Ohio Department of Natural Resources (ODNR) and the Department of Oil and Gas Resources Management (DOGRM) have responsibility for PW in the state of Ohio.

- Ohio Class II SWD Rules:
  - Requires new or converted SWD wells to be certain distances from property boundaries, occupied dwellings, bodies of water, municipal water supplies, and outside the five-year time of travel radius, etc. The five-year time of travel radius is identified as the distance it would take contamination to reach an Ohio Municipal Water Well field in 5-years. Essentially, no Class IID injection wells can be permitted within the five-year time of travel radius around a municipal water well field.
  - Changes to well construction – cement height above the top of the injection zone.
  - Additional testing requirements - higher pressures for MIT testing, 5-year MITs, cement bond logging, etc.
  - Major changes to the area of review (AOR). If injecting more than 1,000 barrels of water per day (bwpd) – 2-mile AOR. Requires corrective action or ownership of wells producing from the same proposed zone for injection in the AOR.

    - Prohibits injection into certain shallower injection zones.
    - Increased timeframes to receive permits and changes from public hearing to public meeting.
    - Complete a new set of rules regarding the construction, testing, monitoring, and operating of Class II SWD surface facilities. Very similar to the Oil and Gas Facility Rules.
    - Elimination of any new Class II annular disposal wells. This was a low-volume disposal method (10 bwpd) that was used by conventional oil and gas operators. Now will require hauling to Class II SWDs for disposal.
    - Additional monitoring and reporting requirements – include quarterly reporting instead of annual reporting and now require manifests for how fluids are received and from where and what operator.

These new Class II SWD rules will make it extremely difficult for putting in a new Ohio SWD well due to the AOR restrictions and potential corrective action within an AOR. This could affect production operations in not only Ohio, but in PA and WV due to their reliance on Ohio for disposal capacity.

- New Ohio Oil and Gas Waste Facility Rules:
    - These are a complete set of totally new rules addressing the recycling of produced or flowback water for reuse, reclamation and recycling of solids, truck wash and clean-outs, and solidification of solids.
    - These new rules address:
        - Permitted locations of Waste Facilities.
        - Design, engineering and drawings, and testing of equipment requirements.
        - Geotechnical work and monitoring well installation and testing.
        - Primary and secondary containment requirements.
        - Monitoring and reporting requirements.
- Brine Hauling:
    - Brine hauling registration, bonding, insurance, and tracking of PW from cradle to grave has been in place in Ohio since 1983, but there have been minor revisions to the laws, but nothing of importance. Brine haulers in Ohio are required to have a daily log and track where and how much fluid (PW or flowback) is received and where it is disposed of for each load. Additionally, there is a reporting requirement on all fluids hauled in each calendar year and submitted to DOGRM.
- Water Tracking - OH does not track water that is recycled for reuse except by registered brine haulers. The registered brine haulers submit annual reports by well, but that data is not available online nor is it published by the Ohio DOGRM.
- Class II disposal volumes are tracked annually and include both conventional and unconventional wells and also include PW from Pennsylvania and West Virginia from the Marcellus Shale. This data is not available online, it must be requested via a public records request. Unconventional shale plays and water production is tracked at the URL: https://ohiodnr.gov/business-and-industry/energy-resources/well-information/production.

2.2.9 Oklahoma

The Oklahoma Corporation Commission (OCC) Oil and Gas Division oversees the development of oil and gas resources as well as PW in the State of Oklahoma.

- Senate Bill 1875, the Oil and Gas Produced Water and Waste Recycling and Reuse Act was signed into law (May 2020)

- SB 1875 states that operators or non-operators have “the right to use, possess, handle, dispose of, transfer, sell, covey, transport, process, recycle, reuse, or treat the produced water and waste and shall have the exclusive right to obtain proceeds for any of the uses of the oil and gas produced water and waste or some portion thereof, including recycled water and treated constituents”.
- SB 1875 gives oil and gas operators ownership of PW until it is transferred to another person or entity. Thus, when PW or waste is transferred to someone else for the purpose of recycling and beneficial reuse, the PW then becomes the property of the person handling the waste. The bill also shields liability from those who plan to process wastewater into recycled water and transport the recycled water for further use in oil and gas operations.
- The intent of the law is to help turn PW into a resource and commodity, instead of a material with previously no economic value.
- Changes to Drilling Permits, Injection Applications, and Simultaneous Injection well permits: [14]
    - Injection Applications
        - ✓ Additional penetrating well information is required to confirm that water will stay in the permitted injection interval.
    - Simultaneous Injection Applications
        - ✓ Elimination of AOR requirement if injection is by gravity flow.
        - ✓ Operators can inject Class II fluids from other wells operated by the same operator if proper permitting is in place.
        - ✓ Requirement for radioactive tracer survey to demonstrate mechanical integrity and containment of fluids before operation on simultaneous injection well.

2.2.10 Pennsylvania

The Pennsylvania Department of Environmental Protection (PADEP) in conjunction with the U.S. EPA oversees the UIC program in Pennsylvania.

There have been no notable changes to PW regulations since the original GWPC report was issued. However, below is a summary of the regulatory authority and framework in PA for the UIC program that may be helpful.

- The U.S. EPA has primary regulatory authority over the nation's injection wells and the State of Pennsylvania is served by U.S. EPA Region III. The PA DEP also requires additional permitting for injection wells and has regulatory authority over any surface facility operations.
- Pursuant to the SDWA and outlined in Part 147 of 40 CFR, the U.S. EPA is the primary regulatory authority for UIC wells, including injection wells specifically permitted for the waste disposal of fluids associated with the oil and gas industry. In the State of Pennsylvania, the U.S. EPA directly implements the UIC Program which is administered by U.S. EPA Region III.
- The State of Pennsylvania, through the PA DEP, also requires a separate Class IID permit to ensure compliance and has direct regulatory authority over all surface facility operations at Class IID injection wells. Chapter 78 regulations (78.18) require two permits for a Class IID injection well in Pennsylvania: A well permit from PA DEP and a UIC permit from U.S. EPA Region III. An application must first be submitted to U.S. EPA Region III and upon issuance of a

[14] Title 165: Corporation Commission Chapter 10: Oil and Gas Conservation Effective October 1, 2020, Last Amended The Oklahoma Register Volume 37 Number 24 September 1, 2020, publication Pages 887 - 2348

permit from U.S. EPA, an applicant must then obtain a well permit from PA DEP under Chapter 78.11. If the well is an existing well being converted to Class IID injection, then PA DEP would re-issue as a "change in use" permit as an injection well with special conditions granting authority under the Solid Waste Management Act and the Clean Streams Law.[15]

- After receiving the initial injection well application package, PA DEP performs a review that includes a geologic analysis based on 25 Pa. Code Section 91.51; a mechanical integrity assessment of the well, including an analysis of the Casing and Cementing Plan; a review of the Control and Disposal Plan to confirm compliance with Section 91.34; and a review of the Erosion and Sedimentation Control Plan to ensure compliance with 25 Pa. Code Chapter 102 and Section 78.53.[16] Additionally, a public hearing is held.
- Historically, PA DEP was primarily concerned with regulating surface activities at Class IID sites. However, Scott Perry, Deputy Secretary of the Office of Oil and Gas Management stated in a September 13, 2021, deposition "that because of this litigation, PA DEP has become aware of regulations which required a more detailed permit review process. This comprehensive consideration now essentially replicates U.S. EPA's review including a review of well integrity, geologic hazards, and waste management along with compliance monitoring."[17]

2.2.11 Texas

The Railroad Commission of Texas (RRC) is responsible for the stewardship of natural resources and the environment, for personal and community safety, as well as the development and economic vitality of energy resources.

2.2.11.1 Produced Water:

- Texas House Bill (HB) 3246, amending Section 122.002 in 2019, was passed to clarify the ownership of PW. This bill provided that any party that takes possession of PW to treat it for a subsequent beneficial use takes title to that water. This helps to clarify the ownership transfer of PW.
- The RRC adopts amendments to §3.30, relating to an MOU between the RRC and the TCEQ. The amendments are adopted to implement changes made by HB 2230 and HB 2771 from the 84th and 86th Texas Legislative Sessions, respectively. The adopted amendments also update the definition of an underground source of drinking water. The RRC received no comments on the proposed amendments.
- HB 2230 (84th Legislature, 2015) enacted Texas Water Code, Section 27.026, to allow dual authorization of Class II and Class V injection wells for the disposal of nonhazardous brine from a desalination operation, or nonhazardous drinking water treatment residuals (DWTR), under the jurisdiction of the TCEQ, into a Class II injection well permitted by the RRC. HB 2230 allows the TCEQ to authorize by individual permit, by general permit, or by rule, a Class V injection well for the disposal of such brine or DWTR in a Class II well permitted by the RRC. New subsection (e)(4)(E) implements the dual authority granted by HB 2230.
- HB 2771 (86th Legislature, 2019) amended Texas Water Code, Section 26.131, to transfer to TCEQ the RRC's responsibilities relating to the regulation of discharges into surface water in the

[15] PA DEP. 2018. Injection Wells for Enhanced Recovery and Disposal Fact Sheet. http://www.depgreenport.state.pa.us/library/GetDocument?docID=47198DocName=8000FS-DEP2250.pdf (accessed October 26, 2022)
[16] ibid
[17] Perry, Scott. 2021. Virtual Deposition 14:18-16:11, September 13, 2021.

state of PW, hydrostatic test water, and gas plant effluent resulting from the exploration, production, and development of oil, natural gas, or geothermal resources. HB 2771 authorizes the transfer of responsibilities from the RRC to the TCEQ after TCEQ receives approval from the EPA to supplement or amend TCEQ's Texas Pollutant Discharge Elimination System (TPDES) program to include authority over these discharges. HB 2771 also established September 1, 2021, as the deadline for TCEQ to submit its request to the EPA to supplement or amend the TPDES program to include delegation of NPDES permit authority for discharges of PW, hydrostatic test water, and gas plant effluent.

2.2.11.2 TX House Bill 3516 (HB 3516) – Adopted Fall of 2022

HB 3516 updates the permitting process for commercial water recycling facilities in TX and directly addresses the H-11 permitting challenges to improve the permitting and construction process. Rules adopted under this section for commercial recycling of fluid oil and as waste must establish:

- Minimum siting standards for fluid recycling pits to provide clarity in order to exclude non-conforming sites.
- Uniform technical, construction, and placement standards provide detailed specifications regarding criteria to expedite the permitting process.
- Uniform standards for estimating closure costs that eliminate ambiguity regarding closure cost estimating procedures.
- Minimum and maximum bonding and financial security amounts based on factors determined by the commission that establish financial parameters sufficient to protect landowners and RRC regarding bonding amount.
- Standards for sampling and analysis of fluid oil and gas waste and provide uniform analytical and sampling guidelines.
- Rather than a permit by rule, a 90-day approval to take place if conditions are met- pending no protest, or variances requested. This expedites the permitting process if all conditions are met (Critical to timeframes).
- In addition, HB 3516 encourages pilot programs for the beneficial reuse of water outside of the O&G market.
- One of the biggest challenges associated with this endeavor has been the lack of defined discharge criteria for PW.
    - Due to the almost infinitely variable chemical composition of PW, discharge standard development appears to be years away.
    - Without established discharge standards and defined success criteria, can make it a challenging environment to obtain investment.
- The Texas Produced Water Consortium (TxPWC) was established on June 18, 2021, by Senate Bill 601 to bring together information and resources to study the economics and technologies related to beneficial uses of PW, including environmental and public health considerations. Texas Tech University, in coordination with the Government Agency Advisory Council and the Stakeholder Advisory Council, serves as administrative oversight for TxPWC.
- The consortium will also develop an economic model for using PW in a way that is economic and efficient and protects public health and the environment.
- To that end, in the fall of 2022, TxPWC submitted a draft report to the legislature regarding recommended rules and guidance for establishing PW permitting and testing standards to better enable the use of PW.

- The TxPWC consortium report covers the cumulative amount of PW available, the type of technologies required to aid in the pursuit of beneficial reuse, and the associated and desired cost for treatment.

2.2.12 Utah

The Utah Division of Oil, Gas, and Mining (UDOGM) ensures access to natural resources in an environmentally responsible manner.

Produced Water in the Uinta Basin:

- Evaluation of Reservoirs, Water Storage Aquifers, and Management Options
  - https://ugspub.nr.utah.gov/publications/bulletins/b-138.pdf
- Emissions of organic compounds from PW ponds: Characteristics and Speciation Technical paper on emissions from PW pits in the Uinta Basin.
  - https://pubmed.ncbi.nlm.nih.gov/29734635/

2.2.13 West Virginia

The West Virginia Department of Environmental Protection (WVDEP) enforces state and federal environmental laws across West Virginia, however, there have been no new regulations issued since 2012.

2.2.14 Wyoming

The Wyoming Oil and Gas Conservation Commission (WOGCC) is primarily charged with preventing the waste of oil and gas resources and protecting correlative rights within Wyoming.

- Appendix H - Additional Requirements Applicable to Produced Water Discharges from Oil and Gas Production Facilities
  - Extensive additions placed on PW discharges.
  - https://casetext.com/regulation/wyoming-administrative-code/agency-020-environmental-quality-dept-of/subagency-0011-water-quality/chapter-2-discharges-permit-regs/appendix-h-additional-requirements-applicable-to-produced-water-discharges-from-oil-and-gas-production-facilities
- Class II Commercial Rule and Well Conversions (WY) - Notes WOGCC can permit and regulate Class II disposals.
  - https://drive.google.com/file/d/1X-2tsu8ty1XG8PLtCC5eQhlGX97h2WjK/view

2.2.15 Additional Multi-State Data Sources

- Multi-State Update on Produced Water (from the Foundation for Natural Resources and Energy Law)
  - April 2021 update on legislative and regulatory developments in New Mexico, Texas, Utah, Wyoming, and Colorado
  - https://www.fnrel.org/-/media/Files/natural-resources-law-network/april-2021/blevins-colclasure-parrot-multi-state-update-on-produced-water-final.pdf?la=en
- Potential Reuse Strategy for High Salinity Produced Water
  - https://iogcc.ok.gov/sites/g/files/gmc836/f/harju_-_potential_reuse_strategy_for_high_salinity_produced_water.pdf

- Analysis of Regulatory Framework for Produced Water Management and Reuse in Major Oil- and Gas-Producing Regions in the United States
    - Analyzes the regulatory framework in major O&G-producing regions surrounding the management of PW, including relevant laws and jurisdictional illustrations of water rules and responsibilities, water quality standards, and PW disposal and current/potential beneficial reuse up to early 2022.
    - https://www.mdpi.com/2073-4441/14/14/2162/htm

2.3 Induced Seismicity

While uncommon, induced seismicity has been associated with well operations in the United States (U.S.) since the 1960s.[18] Only a small fraction of wells in the U.S. are thought to be linked to induced seismic events, however, under the right geologic and operational conditions, any activity which alters subsurface pressure conditions near a critically stressed fault may induce seismic activity.[19] Injection and hydraulic fracturing activities are the well operations most frequently associated with induced seismicity in the U.S., with injection-induced seismicity receiving significant attention from researchers, industry professionals, and state regulators over approximately the last decade.

The primary physical mechanism associated with injection-induced seismicity is the increase of pore pressure at critically stressed fault surfaces, which can initiate slip on a fault (see **Figure 10**). The faults at which this mechanism has been observed are primarily located in the Precambrian basement at depths of five kilometers (km) or more beneath the Earth's surface.[20]

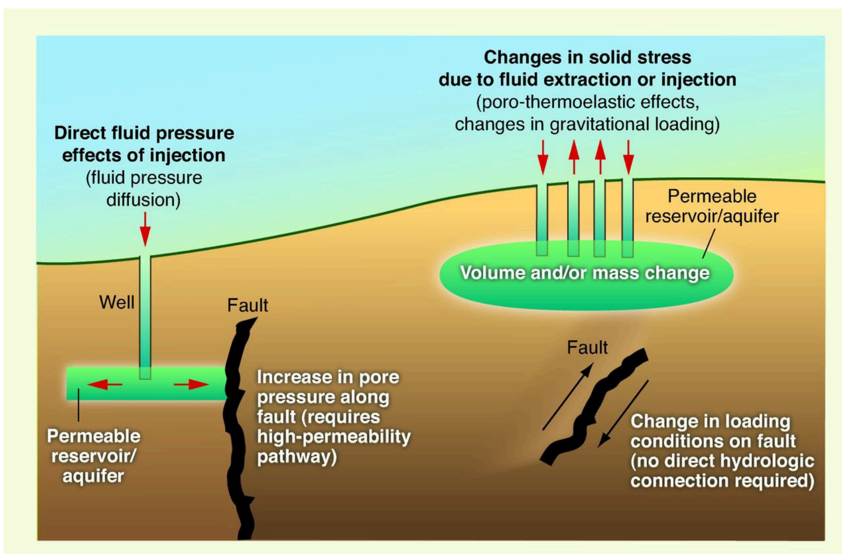

Figure 10: Physical Mechanisms of Injection-Induced Seismicity[21]

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[18] Raleigh, C.B. 1972. Earthquakes and Fluid Injection, American Association of Petroleum Geologists Memoir 18, Underground Waste Management and Environmental Implications.

[19] Induced earthquakes. Induced Earthquakes | U.S. Geological Survey. (n.d.). Retrieved January 9, 2023, from https://www.usgs.gov/programs/earthquake-hazards/science/induced-earthquakes

[20] Ground Water Protection Council and Interstate Oil and Gas Compact Commission. Potential Induced Seismicity Guide: A Resource of Technical and Regulatory Considerations Associated with Fluid Injection, March 2021, 250 pages.

[21] Ellsworth, W. L. (2013). Injection-induced earthquakes. Science, 341(6142). https://doi.org/10.1126/science.1225942

Evaluating and identifying injection-induced seismicity is a difficult process that requires multiple disciplines (seismologists, geologists, reservoir engineers, hydrogeologists, geophysicists, and others) and thorough earthquake, fault, and saltwater disposal (SWD) well data. Davis and Frohlich (1993) established a seven-question screening process for identifying injection-induced seismicity which is still frequently referred to:[22]

1. Are the events the first known earthquakes of this character in the region?
2. Is there a clear (temporal) correlation between injection and seismicity?
3. Are epicenters near wells (within 5 km)?
4. Do some earthquakes occur at or near injection depths?
5. If not, are there known geologic features that may channel flow to the sites of earthquakes?
6. Are changes in well pressures at well bottoms sufficient to encourage seismicity?
7. Are changes in fluid pressure at hypo-central locations sufficient to encourage seismicity?

If all seven questions are answered "yes", one can reasonably conclude that the earthquakes in question have been induced; likewise, if all questions result in "no", the earthquakes are unlikely to be related to injection activity. A combination of "yes" and "no" answers calls for further evaluation and analysis, which can occur in various forms (temporary seismic networks, subsurface fault mapping, reservoir and/or fault modeling, and others), but a clear answer is not always achieved.[23] With this in mind, many states have taken regulatory steps to mitigate the potential for injection-induced events to occur.

2.3.1 Hydraulic Fracturing Induced Seismicity

Hydraulic fracturing-induced seismicity typically results in smaller magnitude seismic events than injection-induced seismicity, and the seismic events from hydraulic fracturing are rarely felt.[24] The largest hydraulic fracturing-related seismic event recorded in the United States was a magnitude (M) 3.5 event that occurred on May 1, 2018, in the Eagle Ford play of Texas.[25]

In comparison to injection at a disposal well, hydraulic fracturing wells usually inject fluid at a higher rate for significantly shorter periods. Fluid is pumped into the well at high rates and pressures in order to exceed the formation fracture gradient, creating fractures and increasing permeability within the formation. Hydraulic fracturing will always result in very small earthquakes, called microseismic events, during successful operations. These microseismic events are often recorded to characterize and image ongoing hydraulic fracturing operations, allowing the operator to better control the extent of fracturing. Individual fracturing stages typically last a matter of hours within a limited spatial area, therefore, induced seismicity resulting from such operations is usually identified by clear temporal and spatial correlations between the hydraulic fracturing operations and resulting seismic events. In addition, hydraulic fracturing operations involve significant data collection during the pre-planning and active operation stages, allowing operators to better characterize the subsurface conditions where seismicity is

[22] Davis, S. D., & Frohlich, C. (1993). Did (or will) fluid injection cause earthquakes? - criteria for a rational assessment. Seismological Research Letters, 64(3-4), 207–224. https://doi.org/10.1785/gssrl.64.3-4.207

[23] ibid

[24] Ground Water Protection Council and Interstate Oil and Gas Compact Commission. Potential Induced Seismicity Guide: A Resource of Technical and Regulatory Considerations Associated with Fluid Injection, March 2021, 250 pages.

[25] Fasola, S. L., Brudzinski, M. R., Skoumal, R. J., Langenkamp, T., Currie, B. S., & Smart, K. J. (2019). Hydraulic fracture injection strategy influences the probability of earthquakes in the eagle ford shale play of south Texas. Geophysical Research Letters, 46(22), 12958–12967. https://doi.org/10.1029/2019gl085167

occurring and identify potentially induced seismic events.[26] Several states have implemented regulatory policies with the goal of limiting the magnitudes of seismic events due to hydraulic fracturing operations.

2.3.2 Injection-Induced Seismicity Over Time

The first established case of injection-induced seismicity in the U.S. occurred at Rocky Mountain Arsenal, CO in the 1960s.[27] A disposal well was completed into the Precambrian basement for the U.S. Army in 1961, for the purpose of disposing of chemical-manufacturing waste fluids. Injection into the Precambrian basement at a depth of 12,000 feet began in 1962, and approximately seven weeks later, a rise in seismicity rate occurred. There was a one-year gap in injection activity from the end of 1963 through late 1964, and the seismicity rate declined during this time. Injection resumed in September of 1964 and peaked in July 1965, coinciding with the peak in seismicity rate in the region. Injection was stopped at the location in February of 1966, yet seismicity continued in the area for approximately 10 years.[28] This case demonstrates clear spatial and temporal correlations between injection into Precambrian basement rock and initial seismic activity, features which are commonly looked for when evaluating potentially injection-induced seismicity in modern times.[29]

Since the Rocky Mountain Arsenal case, other cases of injection-induced seismicity have occurred, and countless cases of potentially injection-induced seismicity have been evaluated.[30] From 2008 to 2015, there was a significant increase in the number of potent injection-induced events in the midcontinental U.S. which were evaluated, many of which were published.[31] Much of the focus in this time frame was on Oklahoma earthquakes (Prague, Love County, Pawnee, and others) thought to be related to the injection of wastewater into the Arbuckle Group and subsequently inducing events within the Precambrian basement. Similar trends were noted with Arbuckle injection in Kansas and Ellenburger injection in Texas, however, no other state experienced as large an increase in the number of events as Oklahoma.[32] Since 2016, the seismicity rate in Oklahoma has been declining per Oklahoma Geological Survey monitoring, in part thanks to the implementation of regulatory requirements by the Oklahoma Corporation Commission (OCC) and a slowdown in oil and gas development activity (see **Figure 11**).[33] While Kansas has experienced a similar decline in seismicity rate to Oklahoma, Texas continues to see increased seismicity rates, often in areas lacking the deep sedimentary injection wells commonly associated with injection-induced seismicity. Researchers continue to investigate the increase in Texas

[26] Ground Water Protection Council and Interstate Oil and Gas Compact Commission. Potential Induced Seismicity Guide: A Resource of Technical and Regulatory Considerations Associated with Fluid Injection, March 2021, 250 pages.

[27] Raleigh, C.B. 1972. Earthquakes and Fluid Injection, American Association of Petroleum Geologists Memoir 18, Underground Waste Management and Environmental Implications.

[28] ibid

[29] Davis, S. D., & Frohlich, C. (1993). Did (or will) fluid injection cause earthquakes? - criteria for a rational assessment. Seismological Research Letters, 64(3-4), 207–224. https://doi.org/10.1785/gssrl.64.3-4.207

[30] Ground Water Protection Council and Interstate Oil and Gas Compact Commission. Potential Induced Seismicity Guide: A Resource of Technical and Regulatory Considerations Associated with Fluid Injection, March 2021, 250 pages.

[31] ibid

[32] ibid

[33] Langenbruch, C., Weingarten, M. & Zoback, M.D. Physics-based forecasting of man-made earthquake hazards in Oklahoma and Kansas. Nat Commun 9, 3946 (2018). https://doi.org/10.1038/s41467-018-06167-4

events with many publications suggesting shallow injection wells, often 10,000 feet or more above the Precambrian basement, being associated with events.[34]

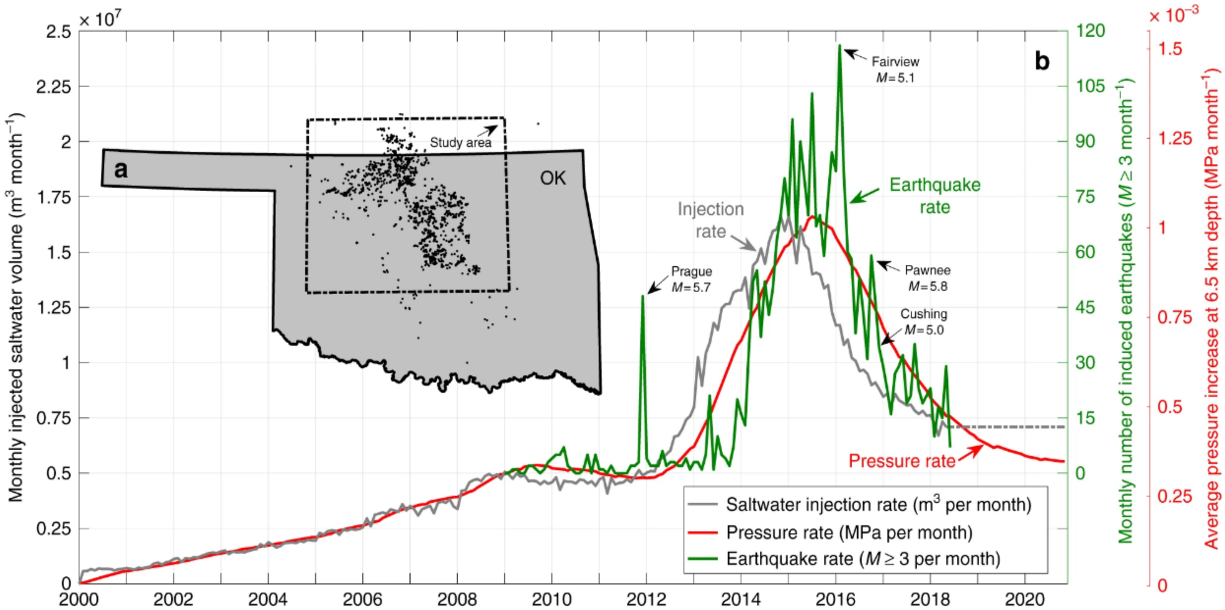

Figure 11: Significant Increase in Oklahoma Seismicity Rate from 2009 – 2015[35]

It is important to note that state regulatory or state geological survey seismic monitoring capabilities and network densities have greatly increased in modern times. Previously, most seismic monitoring was reactive and now has become more proactive in an effort to identify and accurately locate more seismic events. As seismic monitoring capabilities increased, more low-magnitude earthquakes were recorded, regardless of whether more earthquakes are occurring.[36] When evaluating potentially induced seismicity it is important to consider the completeness of the seismic catalog over time and consider that historical catalogs are likely to contain only seismic events which were large enough to be felt or recorded over significant distances.

2.3.3 Induced Seismicity Mitigation

Seismic mitigation can occur in many forms, and many states employ one or more mitigation techniques as a part of regulatory requirements. Some commonly utilized forms of seismic mitigation are briefly described below:[37]

1. Permanent Seismic Monitoring Networks: Permanent seismic monitoring networks, such as that maintained by the USGS, are important for establishing baseline seismicity rates and seismic

[34] Grigoratos, I., Savvaidis, A., & Rathje, E. (2022). Distinguishing the causal factors of induced seismicity in the Delaware Basin: Hydraulic fracturing or wastewater disposal? Seismological Research Letters, 93(5), 2640–2658. https://doi.org/10.1785/0220210320

[35] Langenbruch, C., Weingarten, M. & Zoback, M.D. Physics-based forecasting of man-made earthquake hazards in Oklahoma and Kansas. Nat Commun 9, 3946 (2018). https://doi.org/10.1038/s41467-018-06167-4

[36] Ground Water Protection Council and Interstate Oil and Gas Compact Commission. Potential Induced Seismicity Guide: A Resource of Technical and Regulatory Considerations Associated with Fluid Injection, March 2021, 250 pages.

[37] ibid

hazards in any given region.[38] Earthquake catalogs built from the data recorded by such networks allow regulators and operators to more easily identify when a potentially induced seismic event has occurred.[39] Identifying seismic trends also assists in locating faults, allowing for further characterization of seismic risk and hazard in an area.

2. Temporary Seismic Monitoring Networks: Temporary seismic networks or arrays are often used to proactively monitor new SWDs in local areas where induced seismicity is a high risk. They may also be deployed reactively in areas experiencing abnormal seismicity patterns. Temporary seismic networks are often used in conjunction with traffic light response systems to mitigate induced seismicity and ensure SWD operations are not contributing to seismicity. **Figure 12** presents an example of a temporary seismic network layout.
3. Fault Slip Potential Modeling: Developed and maintained by the Stanford Center for Induced and Triggered Seismicity (SCITS), this publicly available software is used to assess the potential for any given fault to experience slip when undergoing changing pressure and stress conditions due to nearby SWDs.[40]
4. Injection Well Siting: One of the most utilized forms of induced seismicity mitigation, injection well siting practices allow operators and regulators to qualitatively identify the risk involved with a proposed SWD location, based primarily on geological factors such as: depth to Precambrian basement, presence of confining zones, proximity to faulting, and historical seismicity rates. Risk can often be minimized by siting an SWD in a location that is lacking in features typically associated with injection-induced seismicity.

Additional induced seismicity mitigation techniques include, but are not limited to injection rate reductions, injection pressure reductions, seismic hazard mapping, and well logging.

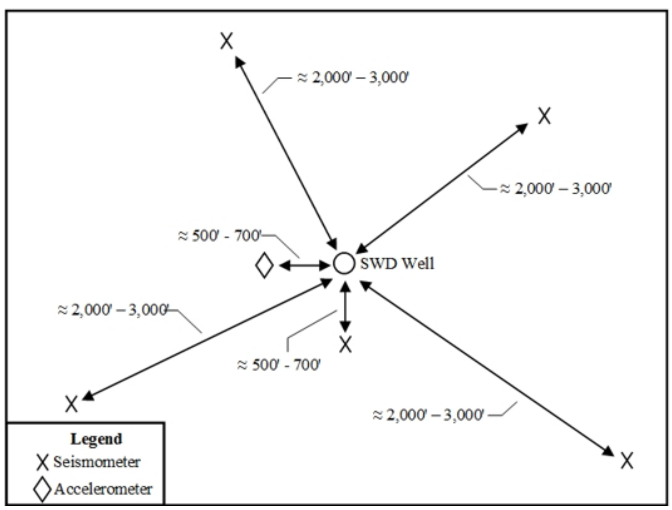

Figure 12: Example of Temporary Seismic Network Layout[41]

[38] Induced earthquakes. Induced Earthquakes | U.S. Geological Survey. (n.d.). Retrieved January 9, 2023, from https://www.usgs.gov/programs/earthquake-hazards/science/induced-earthquakes

[39] Texas seismological network earthquake catalog. (n.d.). Retrieved January 9, 2023, from https://www.beg.utexas.edu/texnet-cisr/texnet/earthquake-catalog

[40] Fault slip potential (FSP). Stanford Center for Induced and Triggered Seismicity. (n.d.). Retrieved January 9, 2023, from https://scits.stanford.edu/fault-slip-potential-fsp

[41] ALL Consulting, LLC, Class II Disposal Well Seismic Monitoring and Mitigation Plan, 2023.

2.4 State Seismicity Regulation

Many states have implemented regulatory measures in recent years, in an attempt to reduce the number of injection-induced seismic events. Common measures include seismic monitoring, rigorous geologic evaluations, and disposal volume restrictions at SWDs.[42] Below are overviews of the regulatory requirements in place for various states across the U.S.

2.4.1 Kansas

The Kansas Corporation Commission (KCC), Kansas Geological Survey (KGS), and Kansas Department of Health and Environment (KDHE) in conjunction utilize a seismic action plan, which is activated when a magnitude two plus (M2.0+) seismic event occurs.[43] When a seismic action plan is triggered, the KGS determines the seismic action score (SAS), which is calculated using risk, clustering, and timing factors to determine the appropriate response. Risk is defined by whether the event was felt and/or within 6 miles of usable structures. Clustering and timing are used to characterize earthquake behavior within 6 miles of an event over the previous 30-day period. Higher clustering and timing scores are more likely to be associated with induced seismic events. If the calculated SAS is above a threshold, or the individual seismic event was M3.5+, KGS, KCC, and KDHE will further evaluate nearby injection wells, faulting, and geologic characteristics to determine whether additional action is required. Additional actions may include:

1. Deployment of temporary seismic arrays,
2. Requirement of more frequent volume reporting by operators, and/or
3. Installment of additional regulatory remediation.

KCC defines areas of concern based on seismic activity and may issue orders to mitigate ongoing seismicity.[44] The orders may require operators to:

1. Verify true vertical depth (TVD) of SWDs,
2. File daily injection reports for all SWDs utilizing the Arbuckle Group, or
3. Limit daily injection rates.

Figure 13 depicts a copy of the Kansas SAS variables table.

[42] Ground Water Protection Council and Interstate Oil and Gas Compact Commission. Potential Induced Seismicity Guide: A Resource of Technical and Regulatory Considerations Associated with Fluid Injection, March 2021, 250 pages.

[43] Kansas Seismic Action Plan. (2014). Retrieved January 9, 2023, from https://www.kgs.ku.edu/PRS/Seismicity/2015/Seismic_Action_Plan.pdf

[44] Induced Seismicity. Kansas Corporation Commission - induced seismicity. (n.d.). Retrieved January 9, 2023, from https://kcc.ks.gov/oil-gas/induced-seismicity

Table 1 – Seismic Scores

	Risk Variables		Clustering Variables			
Score	Felt[1]	Usable Structure[2,3]	Additional Number in Past 30 days[3]	Localized Natural[4] Recursion[3]	Regional Natural[4] Recursion (Kansas Database[5])	Additional # of Events[3] +/- 0.5 Magnitude Over +/- 24 hrs
0	No	No	0	yes	yes	0
1	Yes	Yes	1	no	no	1
2			2			2
3			3			3
4			≥4			4

1 *Based on USGS "Did You Feel It" web site or credible reports*
2 *Based on aerial mapping or field observation of man-made features that can be safely occupied by humans*
3 *Within a 6 mile radius*
4 *Natural from the axiom, for every 100 magnitude 1 seismic event there will be 10 magnitude 2s and 1 magnitude 3 seismic event*
5 *Kansas database includes all earthquakes recorded in Kansas since the 1970s by KGS, USGS, or OGS*

Figure 13: Seismic Action Score Variables[45]

2.4.2 New Mexico

The State of New Mexico Energy, Minerals, and Natural Resources Department, Oil Conservation Division (OCD) oversees the permitting of SWD wells with regard to potential induced seismicity.[46] As part of the permitting process, the OCD requests applicants to conduct a USGS search for historical earthquakes within 100 square miles of a proposed SWD. The OCD may also ask for additional information to demonstrate fluid confinement if conditions exist that increase the risk that fluid may not be confined, or Fault Slip Potential (FSP) modeling to demonstrate the lack of seismic risk from a proposed SWD.

If two M2.5+ events occur within 30 days and within a 10-mile radius of each other OCD may define a Seismic Response Area (SRA) and implement Seismic Response Protocols (SRP).[47] SRA restrictions are currently only applied to deep SWD wells. SRAs are split between 0 to 3, 3 to 6, and 6 to 10-mile buffers with varying injection rate reduction requirements, depending on the event's magnitude. For M3.5+ events, SWD wells within 3 miles are required to shut in. All operators of SWDs within the 10-mile buffer of an SRA are required to:

1. Report weekly injection volumes and average daily surface pressure.
2. Provide analysis identifying the perforated injection interval and formation tops.
3. Monitor M2.5+ seismicity within 10 miles of the SWD using USGS/New Mexico Tech Seismological Observatory (NMTSO) seismic networks.

45 Kansas Seismic Action Plan. (2014). Retrieved January 9, 2023, from https://www.kgs.ku.edu/PRS/Seismicity/2015/Seismic_Action_Plan.pdf
46 NMOCD 2021. Oil Conservation Division Energy Minerals and Natural Resources Department State of New Mexico. Seismicity Response Protocol. December 20, 2021.
47 Ibid

SRA restriction protocol is currently a request from OCD, not a requirement.[48] However, OCD stated they have the authority to issue Orders for operators to comply with restrictions if deemed necessary. **Figure 14** provides the Category 2 SRPs effective with one M3.0+ event.

Category 2: Seismicity Response Protocol:

Effective with one M3.0+ Event

M3.0+ event	M3.5+ event
All Category 1 Monitoring & Reporting protocols, and o 50% rate reduction within 0-3 miles o 25% reduction between 3-6 miles o Reductions to rate should start immediately and be completed within a week o Notify OCD of pertinent information within 24 hours or next business day, whichever is latest, of an event using the OCD form.	**All Category 1 Monitoring & Reporting protocols, and** o Shut in at 0-3 miles o 50% rate reduction at 3-6 miles o 25% rate reduction at 6-10 miles o Reductions to rate should start immediately and be completed within a week o Notify OCD of pertinent information within 24 hours or next business day, whichever is latest, of an event using the OCD form.

Figure 14: New Mexico Seismic Response Protocol Category 2[49]

2.4.3 Ohio

2.4.3.1 Injection Regulations

The Ohio Department of Natural Resources (ODNR), Division of Oil & Gas Resource Management (DOGRM) oversees the permitting of SWD wells.[50] The UIC staff examines every application to verify that the site-specific conditions of each proposed SWD are met. Specific site permit conditions may be applied to address site-specific circumstances.[51] The permit AOR radius is based on the proposed daily injection volume, permits requesting 200 barrels/day or less use an AOR radius of ¼ mile, while permits requesting greater than 200 barrels/day use a ½ mile AOR radius.

With regards to reporting SWD operators are required to monitor injection pressure and volume daily, with average and maximum pressures and volumes compiled monthly for submission. Since 2014, new operators are required to continuously monitor injection and annulus pressures.

For earthquake response, Ohio utilizes a traffic light system, where regulatory action is dependent on factors such as event magnitude, elastic properties of the near-surface, and proximity to population centers and critical structures. Beyond the traffic light systems curtailments, the division may request

[48] Email conversation with NMOCD representative. May 5, 2022.

[49] NMOCD 2021. Oil Conservation Division Energy Minerals and Natural Resources Department State of New Mexico. Seismicity Response Protocol. December 20, 2021.

[50] ODNR, New rules - class II disposal wells and oil and Gas Waste Facilities. (n.d.). Retrieved January 27, 2023, from https://ohiodnr.gov/discover-and-learn/safety-conservation/about-odnr/oil-gas/oil-gas-resources/new-rules-c2dw-ogwf

[51] Ground Water Protection Council and Interstate Oil and Gas Compact Commission. Potential Induced Seismicity Guide: A Resource of Technical and Regulatory Considerations Associated with Fluid Injection, March 2021, 250 pages.

additional alterations to operational measures including added seismic monitoring, rate and pressure reductions, and construction modifications.

2.4.3.2 Hydraulic Fracturing Regulations

With regard to hydraulic fracturing permits the division staff reviews construction, engineering, and geological data prior to issuing permits for horizontal wells. Specific permit conditions may be applied to wells drilled near faults or areas of known seismic activity, including the requirement for temporary seismic monitoring prior to and during operations.[52] The AOR review uses three-mile buffer zones around known Precambrian faults and recorded seismic events to determine whether special seismic monitoring conditions will be applied to a permit. Wells near urbanized areas may be subject to additional permit conditions due to the increased risk factors associated with higher population density areas. Additionally, the Ohio law requires operators to submit wireline electric logs, well completion records, stimulation fluid chemical data, and quarterly production reports at hydraulic fracturing wells.

Ohio employs a Traffic Light System with regard to induced seismic activities. Action levels for induced seismicity due to hydraulic fracturing in Ohio are detailed below:

- **Magnitude > 1.5:** Direct communication begins between Division and the operator.
- **Magnitude 2.0 – 2.4:** The operator must work with Division to modify operations.
- **Magnitude > 2.4:** Temporary halt on lateral completions, operator must receive approval plan from Division to resume completion operations.

Several mitigation techniques may be utilized when induced seismicity occurs during hydraulic fracturing. These can include changing from zipper fracking to stack fracking, reduction of 20% or more in volume and/or pressure, skipping stages, and switching to a smaller sieve size.

2.4.4 Oklahoma

2.4.4.1 Injection Regulations

The Oklahoma Corporation Commission (OCC) administers SWD well permitting and if induced seismicity concerns are present, OCC may require additional information during the SWD permitting process.[53] This additional information may include historical earthquake analysis, additional geological and/or geophysical investigations, and reservoir modeling. In addition, OCC may require additional permit conditions be added to an injection order prior to issuance of the order, often relating to the limiting or suspending of injection activity following seismic events.[54] OCC has also prohibited new injection wells into some of the shallower Permian formations in western Oklahoma due to alleged saltwater purges at the surface.

In areas where seismic concern exists, up to a 10-mile radius AOR may be used for seismic review, and specific geologic intervals thought to be associated with the increased seismic hazard, such as the

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[52] Ground Water Protection Council and Interstate Oil and Gas Compact Commission. Potential Induced Seismicity Guide: A Resource of Technical and Regulatory Considerations Associated with Fluid Injection, March 2021, 250 pages.
[53] ibid.
[54] Induced Seismicity & UIC Department. Oklahoma Corporation Commission. (n.d.). Retrieved January 9, 2023, from https://oklahoma.gov/occ/divisions/oil-gas/induced-seismicity-and-uic-department.htmlforecasting

Arbuckle Group, may be restricted or denied. Furthermore, injection volumes and pressures are required to be recorded daily and reported to OCC weekly.[55] In some cases, reporting may be required daily. OCC may also request additional mechanical integrity testing (MIT) at any time in areas of concern.

OCC responds to potentially induced seismic events with Area of Interest (AOI) directives, limiting SWD operations when large earthquakes (M4.0+) or large numbers of smaller events (M3.0+) occur.[56] Such directives generally apply restrictions based on proximity to events, such as:

- **Inner Zone (3-5 miles):** Typically requires SWD shut-in.
- **Intermediate Zone (5-10 miles):** Typically requires injection volume reduction.
- **Outer Zone (10-20 miles):** Typically limits wells to previously reported volumes and notice is given for potential future reductions.

The directive actions described above are general in nature and often vary by area and perceived hazard. Additional actions prescribed may include plugging back from the Precambrian basement and diagnostic testing, such as Radioactive Tracer Surveys (RTS), to demonstrate injectate does not reach the Precambrian basement. **Figure 15** depicts Oklahoma seismic areas of interest and SWD well locations.

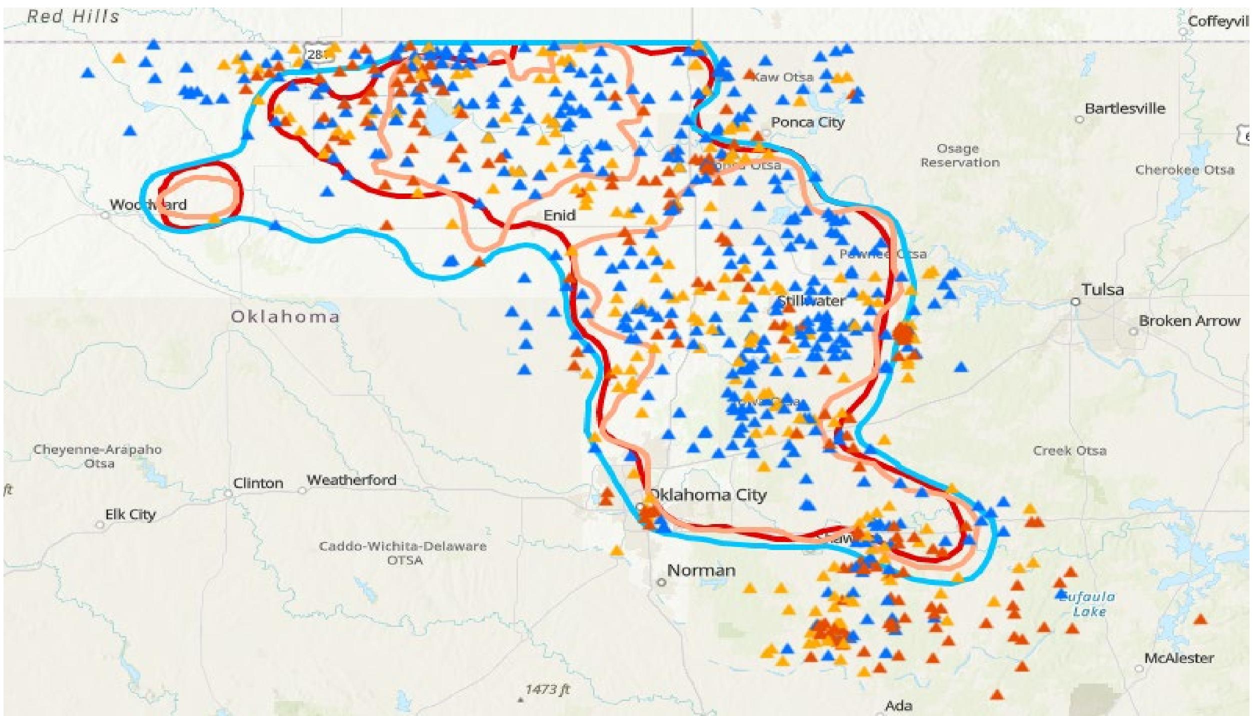

Figure 15: Oklahoma Seismic Areas of Interest and Saltwater Disposal Well Locations[57]

[55] Well Completion Seismicity Protocol. Oklahoma Corporation Commission. (February 27, 2018).

[56] Response to Oklahoma earthquakes. Oklahoma Corporation Commission. (n.d.). Retrieved January 9, 2023, from https://oklahoma.gov/occ/divisions/oil-gas/induced-seismicity-and-uic-department/response-oklahoma-earthquakes.html

[57] Induced Seismicity & UIC Department. Oklahoma Corporation Commission. (n.d.). Retrieved January 9, 2023, from https://oklahoma.gov/occ/divisions/oil-gas/induced-seismicity-and-uic-department.html

2.4.4.2 Hydraulic Fracturing Regulations

The permitting process for hydraulic fracturing wells in Oklahoma involves typical well permitting requirements to protect underground sources of drinking water (USDW), the environment, and to prevent waste. For specific plays (e.g., the SCOOP-STACK), the OCC may require additional seismicity-related permit conditions within an AOI, such as active monitoring. Additionally, operators are expected to complete thorough pre-planning, including seismic investigation of the area in which hydraulic fracturing operations are to be completed. During active hydraulic fracturing operations, operators are expected to notify OCC of any events that occur within 5 km of a stimulated well. In addition, operators are expected to submit Form 6000NHF – Notice of Hydraulic Fracturing, which includes operators planned actions to mitigate felt seismicity, prior to beginning completion operations. At any time, division staff may ask for detailed completion information, the operator’s Seismicity Response Plan, and preplanning seismicity data (geologic, geophysical, seismic) should seismicity occur during operations.

Division staff requires operators conducting hydraulic fracturing operations in the SCOOP-STACK area to have access to a monitoring array providing real-time data and to respond to events in accordance with a Traffic Light System as follows:

- **Magnitude > 2.0:** Operators begin to follow their Seismicity Response Plan.
- **Magnitude > 2.5:** Pause for no less than six hours, and discussion of further mitigation efforts with Induced Seismicity Department staff by phone, email, or other approved method.
- **Magnitude > 3.0:** Same as for magnitude > 2.5 events, however, operations cannot proceed after the mandatory pause without induced Seismicity Department staff approval.
- **Magnitude > 3.5:** Operations cease immediately. Operators must meet with Induced Seismicity Department staff for a technical review of the operations and may be required to submit additional detailed information regarding both the stimulation and resulting seismicity. Operations may only restart with the Seismicity Department manager’s approval of a new operational mitigation plan and a return to baseline seismicity levels in the areas of concern.

Operational mitigation procedures are determined on a case-by-case basis, but may include some combination of the following options:

- Pausing, or no pressure pumping, for 6 to 24 hours
- Reducing fluid volumes and/or pump rates for subsequent stages
- Changing fluid design for subsequent stages
- Reducing the length and total fluid volume of subsequent stages
- Skipping subsequent stages

2.4.5 Pennsylvania

The Commonwealth of Pennsylvania, Department of Environmental Protection (PADEP) manages the state’s seismic response to SWD operations. However, an operator must first apply for and receive a Class IID injection permit from U.S. EPA Region III, as Pennsylvania does not have primacy of its UIC Program. PADEP may apply special permit conditions at proposed SWD locations of seismic concern.[58] The typical special permit conditions applied are in the form of Seismic Monitoring and Mitigation Plans (SMMPs) and traffic light response systems. The purpose of an SMMP is to establish a local seismic

[58] Underground injection control wells. Department of Environmental Protection. (n.d.). Retrieved January 9, 2023, from https://www.dep.pa.gov/Business/Energy/OilandGasPrograms/OilandGasMgmt/Pages/Underground-Injection-Wells.aspx

monitoring network to be installed at a proposed SWD location prior to injection commencement. The SMMP is to detail monitoring hardware, data collection, equipment maintenance, event mitigation planning, and reporting requirements.

The traffic light response system determines the earthquake response actions depending on the source, magnitude, distance, and frequency of events observed. Seismic events determined not to be injection-induced require no change to operations. If three or more injection-induced events between M1.0 and M2.0 occur within two miles of the SWD within a seven-day period, injection rates must be reduced by 50% until further notice. If an M2.0+ event occurs within two miles of the SWD, all injection activities must be terminated within 48 hours of the event. Assessment and evaluation of the event will be undertaken, and additional actions will be considered. Return to normal operating conditions is possible only after a complete evaluation and analysis of the event, with PADEP approval. **Figure 16** shows the PADEP traffic light response system.

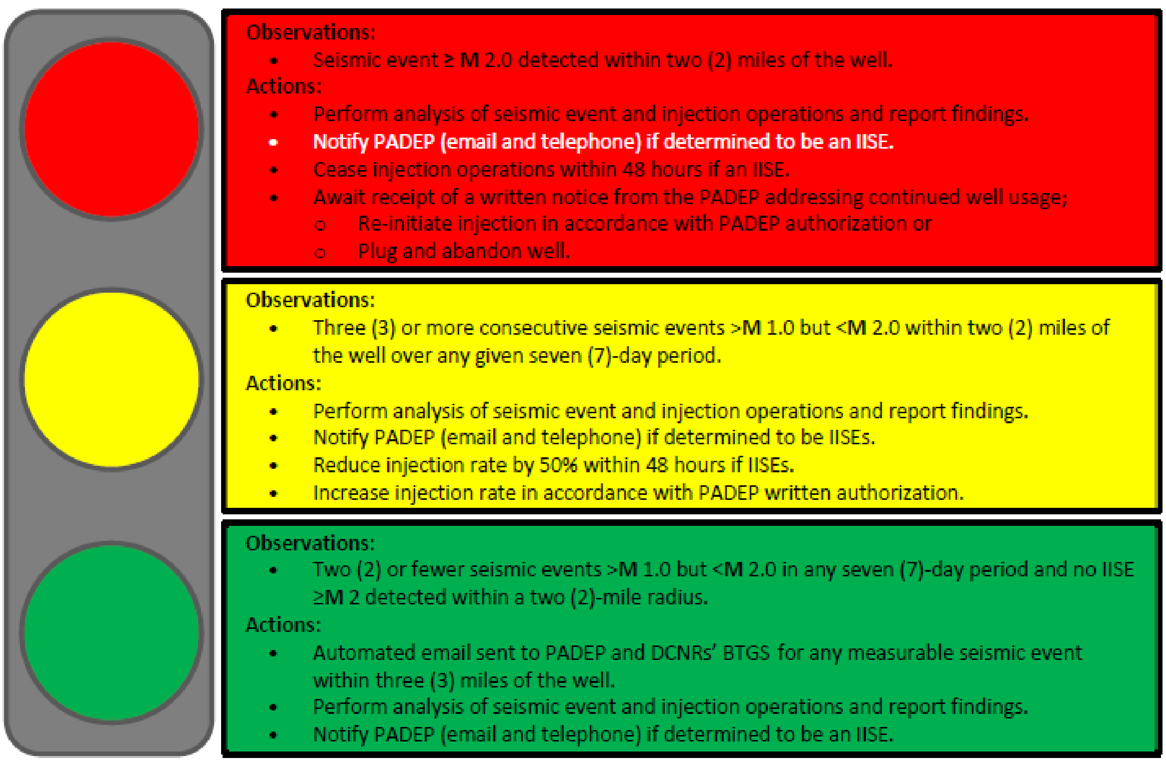

Figure 16: Pennsylvania Traffic Light Response System[59]

2.4.6 Texas

The Texas Railroad Commission (RRC) includes a seismic review with general SWD permit applications.[60] Applicants are required to conduct USGS and TexNet searches for historical earthquakes within 100 square miles of a proposed SWDs. The RRC has the authority to suspend, terminate, or modify a disposal well permit if a well is thought to be contributing to seismic activity. They also require operators to

[59] ALL Consulting, LLC, Class II Disposal Well Seismic Monitoring and Mitigation Plan, 2023.

[60] Seismicity response. (n.d.). Retrieved January 9, 2023, from https://www.rrc.texas.gov/oil-and-gas/applications-and-permits/injection-storage-permits/oil-and-gas-waste-disposal/injection-disposal-permit-procedures/seismicity-review/

disclose annual volume and pressure data or may stipulate more frequent reporting if the staff sees a need for additional information. Additionally, the RRC may ask for additional information in the general SWD application to demonstrate fluid confinement if conditions exist that increase the risk that fluid may not be confined.

In 2019 the RRC issued guidelines that dictate additional considerations for proposed SWDs in the Permian Basin.[61] These considerations include initial seismic review, where any event M2.0+ within 100 square miles of the proposed SWD may trigger further RRC review; request for additional information, such as disposal zone conditions, adjacent strata, step rate test results, and bottom hole pressure data for proposed SWDs with seismic events within the AOR; as well as, well-by-well seismic grading and classifications, which ultimately determine permit viability and maximum allowable injection rate and are based on:

- Number of seismic events M2.0+ within AOR
- Number of seismic events M3.0+ within AOR
- Distance to nearest fault
- Distance to nearest M2.0+ seismic event
- Years since the last M2.0+ event within AOR
- Number of faults within AOR
- Highest Recorded magnitude event within AOR
- Depth to Precambrian basement.

The RRC may also request fault slip potential modeling in areas of seismic concern. However, operators may receive greater operating limits with the submittal of an RRC-approved Seismic Monitoring Plan and an Earthquake Response Plan.

With regards to earthquake response, the RRC utilizes a traffic light system, without specific thresholds, to allow flexibility in responsive actions depending on event characteristics and location.[62] Following seismic events M3.5+, the RRC seismologist may designate a Seismic Response Area (SRA), as deemed appropriate, where additional seismic response approaches will be implemented.[63] During a response, RRC staff may request additional information, such as:

- Monthly SWD information for the year prior to the seismic event, and monthly updates following the event,
- Review of current and pending drilling permits,
- District office inspections of wells in the SRA, and
- Other information or actions as deemed necessary.

Upon designation of an SRA, operators of SWDs within the SRA will be required to reduce maximum daily injection volumes and pressures as determined appropriate by the RRC. These actions will be suggested as voluntary actions per RRC, and any operator declining to take voluntary action may result

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[61] Response Plan to Seismic Events in Texas. Texas Railroad Commission. (January 2022). Retrieved January 9, 2023, from https://www.rrc.texas.gov/media/buhgzt0o/2022-01-31_seismic_response_sog_final.pdf

[62] ibid

[63] Seismicity response. (n.d.). Retrieved January 9, 2023, from https://www.rrc.texas.gov/oil-and-gas/applications-and-permits/injection-storage-permits/oil-and-gas-waste-disposal/injection-disposal-permit-procedures/seismicity-review/seismicity-response/

in RRC pursuing permit modifications, suspension, or termination. Suggested SRA actions may differ based on SWD classification (e.g., deep, or shallow).[64] **Figure 17** shows SRAs with corresponding seismic events in the Permian Basin.

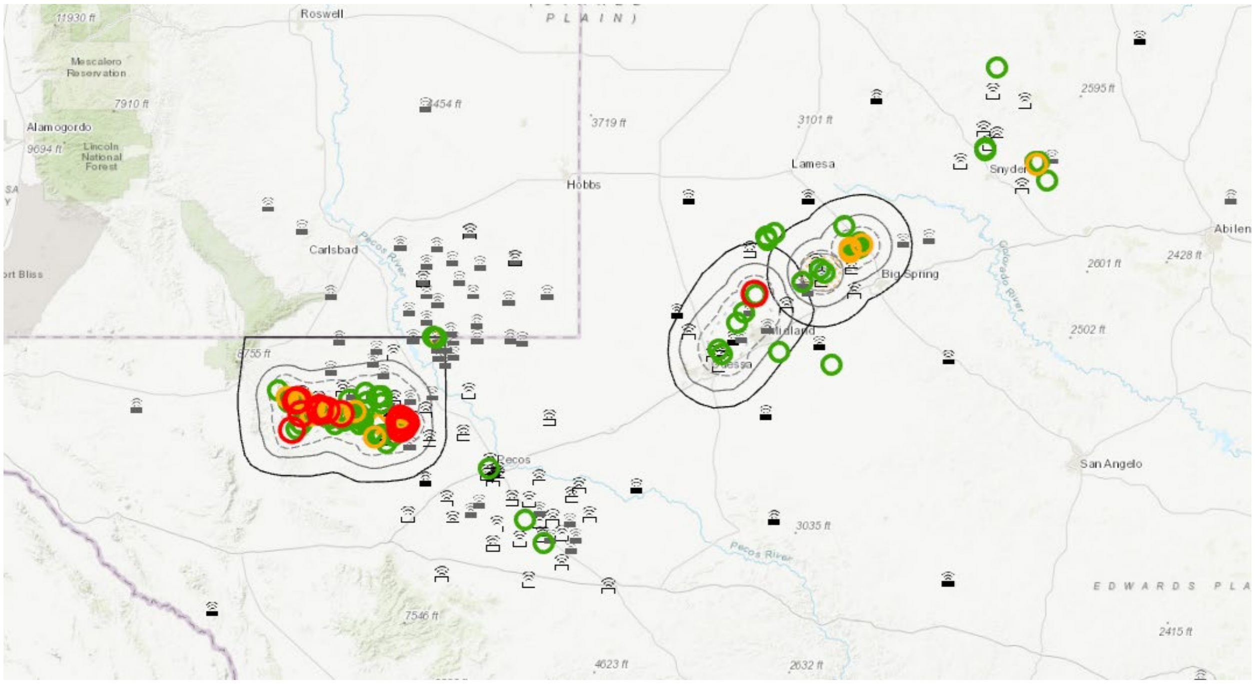

Figure 17: RRC Seismic Response Areas and 2022 Texas Seismic Events M3.0+[65]

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[64] Seismicity response. (n.d.). Retrieved January 9, 2023, from https://www.rrc.texas.gov/oil-and-gas/applications-and-permits/injection-storage-permits/oil-and-gas-waste-disposal/injection-disposal-permit-procedures/seismicity-review/seismicity-response/

[65] Texas seismological network earthquake catalog. (n.d.). Retrieved January 9, 2023, from https://www.beg.utexas.edu/texnet-cisr/texnet/earthquake-catalog

3 Notable Changes in PW Operational and Management Practices

The focus of this section is to identify the most notable changes in PW operational and management practices in each region. As mentioned earlier, out of the seven development regions, the four largest and most prolific areas associated with readily available PW data include the Permian, Eagle Ford, Appalachian, and Bakken.

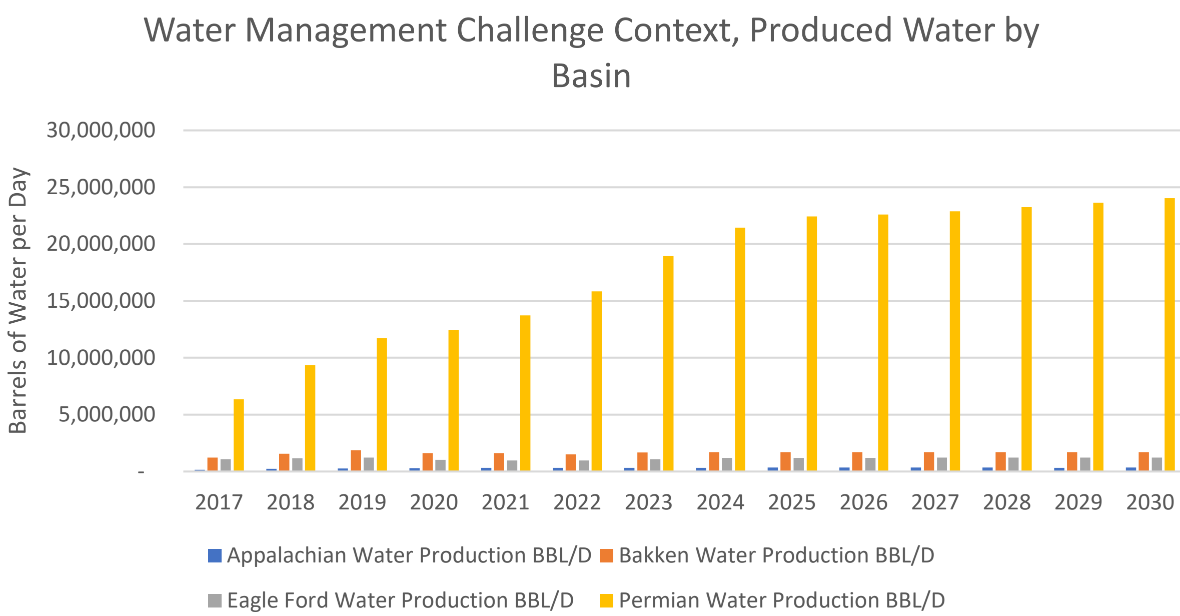

Figure 18: Daily PW Volumes 2017 – 2030 Appalachian, Bakken, Eagle Ford, Permian Basins[66]

The bar chart in **Figure 18** depicts the daily PW volumes from 2017 to 2030 for the four basins and demonstrates the immense challenge facing the Permian Basin as compared to all other development regions combined. The Permian currently produces more than 10.5 times the volume of water daily than the Bakken, 16.4 times as much as the Eagle Ford, and 49 times more than the Appalachian. That difference is projected to become greater in the future, until 2030 when the Permian outpaces the other basins by the following multipliers - Bakken 14.1, Eagle Ford 19.6, and the Appalachian 69.1.

3.1 Permian – Nexus for Produced Water

As mentioned earlier, the confluence of high levels of oil production and corresponding PW volumes within a landlocked area with high current and projected levels of water scarcity makes the Permian a key location for all aspects of PW management, disposal, recycling, regulatory advancement, and beneficial reuse activities and its associated research. As the focus of stakeholders across the country has converged on the Permian in these areas, along with other development regions slow to make significant changes or advances in this since the previous report was issued, this report update heavily focuses on the Permian Development Region.

[66] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

Unconventional oil and gas development is in full swing in the Permian Basin of New Mexico and Texas, and recent worldly events only briefly slowed production gains in this most important of onshore plays. Energy Information Administration (EIA) says cumulative production in 2022 is now over 5MM BOPD, and operators with mineral interests in the best acreage in the play are ramping up drilling, completion, and production activities to meet post-pandemic global demand. However, one of the largest factors standing in the way of a truly booming Permian Basin is PW management and disposition.,

Within the extent of the Permian are two sub-basins with distinct geologic characteristics—the Delaware and Midland basins—including depth, porosity, and water cut. The two sub-basins also happen to straddle state lines, which sets up differing regulatory frameworks for hydrocarbon production and PW management.

Oil and gas production streams include the two hydrocarbons and salt water, which is concentrated enough that it cannot be discharged to the surface and is most often injected underground in permitted SWD wells. Estimates put the production ratio of water barrels to hydrocarbons barrels anywhere from 2:1 to 8:1. In the first half of 2022, the average production of PW across the entire Permian basin was over 15MM bbls/day (barrels per day), this volume must be trucked or piped to the approximately 2,100 permitted SWD wells within the basin's borders. However, PW conveyance comes at a cost, either of pipeline construction or hauling, and those expenses can quickly impact well economics. Consequently, PW transport alone has created an entire auxiliary industry (Water Mid-stream) of service companies to handle these increasing volumes.

Aside from disposal, many operators and service companies are continuing to develop and test water reuse technologies. But the sheer volume of PW limits its treatment and reuse viability, and some estimates peg reuse at only around 30%. Treatment costs are the second constraining factor, and because these processes are still expensive, injection will likely remain the dominant method for the disposition of PW within the basin for the near term.

Another cap on Permian growth is induced seismicity. Seismic events in the Basin have ticked up in number and magnitude since the early 2010s, and some observers note this upward trend correlates with the increased exploration and production activity in the basin since PW is most often disposed of via underground injection. The scientific community and government agencies such as the USGS continue digging into the data to understand if deep injection is influencing the current uptrend in seismic activity within the basin.

State agencies in Texas and New Mexico have noted the trend and put in place restrictions in areas of concern, or Seismic Response Areas (SRAs). In late, 2021, agencies requested SWD operators limit injection rates in areas where seismic activity had increased. While participation was ultimately voluntary, operators have generally agreed to cooperate to avoid more serious enforcement action such as total facility closure. The establishment of these SRAs in Texas has resulted in a nearly 300,000 bwpd curtailment of permitted injection. Operators with historic injection into deeper formations are also looking at recompletion in shallower formations to temper potential seismic impacts.

The establishment of SRAs will undoubtedly affect exploration and production well economics. Finding alternate disposal locations for millions of barrels of PW is expensive. Estimates put displaced barrels at over 2MM for the Midland sub-basin, and 2.5MM for the Delaware sub-basin monthly. Numbers are similar for New Mexico SRAs, where estimates range from around 2MM bbls to 4MM bbls. To fully realize the impact SRAs have on operators, it's important to first note permitted disposal capacity limitations.

Upon application for a permit to inject, state agencies assess data presented in the application from analogous wells of the target injection formation to assign operators a maximum allowable surface injection pressure (MASP). That number correlates with a bbls/day value, and both producers and disposal well operators plan production, in part, based on their ability to handle PW. But because of formation pressure fluctuations, surface pressures occasionally max out before the corresponding daily volume is reached. Thus, data suggest SRA curtailment is forcing operators in the core acreage of the Permian to re-examine the calculus of daily injection volumes.

Data also suggests SRAs have had the intended impact. Seismicity in the Gardendale SRA near Midland has decreased since late 2021, with seismic events greater than M2.0 reduced by over 25% from the third to the fourth quarter of that year. And magnitude also showed a downward trend, with only 22 incidents greater than M2.0 in early 2022. With this demonstration of the efficacy of regulatory mandates, operators are being forced to explore alternatives to injection for PW disposal. For example, operators and service providers are redoubling water reuse and recycling efforts, examining the viability of injection in shallower zones, and continuing to build out pipelines to more evenly distribute wastewater outside of SRA boundaries. Of course, these activities come at a cost.

It could be argued the financial consequences of SRAs and other in-kind agency mandates are just beginning, but operators agree the cost of responsible PW management will continue to grow. When SRAs mandates first happened, some SWD operators began disposing at higher rates than normal to max out or utilize all of their permitted capacity. However, actual operational capacity and permitted capacities differ, hence this approach is not sustainable. One PW projection for the Permian shows that an additional 2.5MM barrels of disposal capacity is necessary in the Delaware sub-basin by 2026. That translates to about 100 new disposal wells, at a cost of around $400MM.

Construction of new pipelines for additional water takeaway volumes is expensive but may be a necessary countermeasure for curtailment mandates. Potential synergies exist, however, if operators could find ways to connect existing infrastructure and share costs, but as logical as sharing infrastructure seems, planning and scheduling of water takeaway becomes riskier. Also, depending on reservoir quality in areas being developed, drilling activity might shift away from overbuilt pipeline systems, further degrading rates of return. Linear asset development means obtaining rights-of-way with surface owners, which is an additional cost to construction labor and materials.

Operators might be able to capitalize on SRA curtailments by evaluating injection feasibility in shallower zones, which require less capital to drill and complete. That option is less appealing and potentially problematic, however, for producers who must drill through these pressurized shallow zones and cement surface casing. In some cases, additional casing strings are necessary to neutralize pressure in the shallow zones, at an average cost of half a million dollars and additional rig time.

State regulatory frameworks for PW management in Texas and New Mexico differ such that Permian operators are always adapting. With the highest quality Permian reservoir in New Mexico, development has been continual and extensive, which has meant the need for more disposal wells. As it happens, permit lead times in New Mexico are significantly longer than in Texas, and permit stipulations are more onerous. In some cases, delays in permitting have forced New Mexico operators to send water across the border to Texas. In fact, an approximated one-third of PW from New Mexico is conveyed via truck or pipeline to Texas.

SRA implementation made adaptation to state PW management yet more involved. To control costs, operators will utilize all available permitted disposal capacity because conveying water across state lines might not always be an option. And there's evidence, regulators in New Mexico and Texas are cooperating. The states are each party to a memorandum of understanding (MOU) to work together on striking a balance between economic disposal and induced seismicity.

PW re-use is the most likely outcome of state-mandated disposal limitations, and operators and service companies continue to innovate in this space of the market. Operators are already coordinating to send wastewater where it can be re-used in some manner before disposal, and data science begets maximized efficiency. New data platforms are allowing operators to share drilling and completion schedules and broadcast available PW volumes most efficiently in real-time. It is these kinds of efficiencies helping operators polish their ESG metrics while saving time and money.

Dynamic conveyance of PW around the Permian Basin is crucial to the profitability of operators. As previously mentioned, a number of new pipeline projects are on paper and being vetted for construction because they are the ideal logistical workaround to SRAs. In addition, significant volumes of PW are being piped from the southern border of New Mexico into Texas where there is additional disposal capacity often within close proximity to the producing wells.

As previously mentioned, permitted disposal capacity can be illusory because wells often reach the maximum allowable surface injection pressure (MASP) before their permitted capacity in bbls/day. If development is to even remain flat, more SWD wells will be needed to accommodate planned modern drilling programs in the Delaware sub-basin. Some data suggests operators and service companies are sitting on over 40MM bwpd in permitted but undrilled disposal well capacity. With the advent of SRAs, it is clear these new permits must be completed to economically manage water in the basin.

With such challenges for PW management, industry coalitions such as the New Mexico and Texas Produced Water Consortiums are continuing to communicate on the possibilities for the beneficial re-use of PW outside of the industry, including surface discharge. Central topics include the latest technologies and regulatory and legal frameworks for the responsible management of PW. The ever-present hurdle is cost control, and investment in PW management now is important as ever. Until recently, investment in reuse was occasionally too risky a bet for investors because of questions about scale, cost of R&D, and fluctuating oil prices, but circumstances are shifting.

Return on capital is now a central focus of publicly traded E&P companies, and operators have shifted away from growth at any cost to operating within free cash flow. High commodity prices have lifted the long-term outlook for the industry and answering the call for affordable energy presents outside investors with multiple chances to capitalize on the need for expanded offerings in PW management.

Investors must be assured regulatory agencies in New Mexico and Texas are working together to create sound, logical frameworks for the industry. Cooperation is occurring but significant policy differences remain. Similarly, federal policies governing the development of the federal mineral estate also require modernization. If novel beneficial re-uses such as surface discharge are to ever become commonplace, PW testing and safety standards will require universality.

Original PW recycling rules in TX were well-intentioned and resulted in significant operator-based recycling efforts. These rules resulted in a streamlined ability for leaseholders/operators of record to recycle water for upcoming completion operations in the form of a “Non-Commercial Recycling Facility Permit.” Alternatively, the commercial recycling permitting process significantly hampered commercial recycling efforts due to cumbersome and un-timely processes/approvals often taking up to 2 years for approval. Market conditions for PW in the Permian Basin necessitated changes to the commercial recycling process in order to streamline permitting efforts by third-party water mid-stream companies. Due to the high levels of activity, PW has transitioned from a waste product destined primarily for downhole disposal, to a commodity to be used for upcoming completions, EOR, or beneficial reuse.

This challenge for commercial operations was compounded by high-intensity simul-frac designs combined with high water-cut demands and the need for excess high-volume storage. In order to facilitate these demands, water mid-stream companies required exacting concise permitting/construction guidelines and time-frames for permitting that were compounded by the challenge of ever-evolving drilling plans. The promise of HB 3516 is to improve the H-11 permitting and construction process to alleviate these challenges.

SRAs appear to be having the impact regulators in New Mexico and Texas intended. Seismicity in established areas is dropping, but a real consequence of the curtailments is the displacement of millions of barrels of PW. Operators have been forced to develop alternate disposal plans for those barrels to ensure production goals are met and completion plans aren’t stalled. As more and more new wells are brought online in the coming years, projections show some 6MM additional barrels of PW needing disposal. That will bring the total PW in the basin to around 20MM bbls/day. To offset those volumes, re-use and other alternatives to injection would have to increase to levels that are currently viewed as being unrealistic. **Figure 19** exemplifies the foreseen management issues in the Permian by showing the anticipated water forecast through 2026.

Induced seismicity and the regulations brought on will continue to challenge operators managing PW. While alternatives to deep injection exist, the cost of sending PW greater distances from where it was produced will increase. There is much promise for expanded re-use within and outside of the industry, injection in shallower zones, and construction of new pipelines.

Collaboration and cooperation between industry and governing agencies will be crucial to the longevity of the Permian Basin. Regulators at the state and federal levels must pledge to develop homogeneous policies to control and prevent induced seismicity. Given the fundamental need for reliable energy at home and around the world, not to mention the current price commodity environment, all stakeholders must come together on a sustainable future for the Permian.

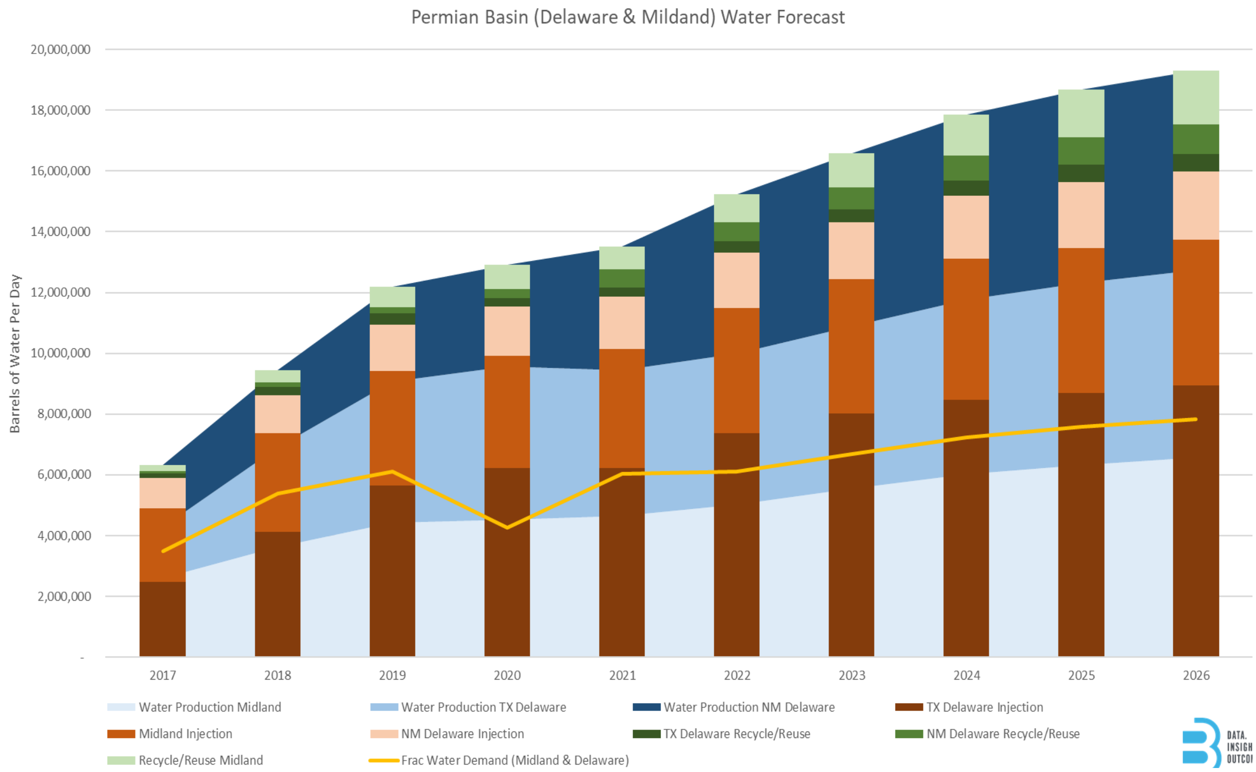

Figure 19: Permian Basin Water Forecast 2017 - 2026[67]

3.1.1 Permian – Produced Water Market Profile and Analysis

The bar chart in **Figure 20** depicts and projects the daily volume of PW in barrels per annum in the Permian Basin Development Region from 2017 through 2030. As one can see a steadily increasing volume in PW is predicted. This daily volume is compared to the daily injection volume and recycle quantities available or forecasted per year. Finally, the demand for water to be used for fracking operations is graphed in barrels per day (bbls/day) as well, indicating either a shortfall or abundance of recycled water available to meet this demand.

Permian Basin delivers excess volumes of PW versus the current and projected frac demand. PW volumes have surpassed demand by ~50% since 2017, although the frac demand doubled to over 6,600,000 bbls/day in 2022, the PW volume has more than kept pace with this growth and topped demand by approximately 60% in 2022. This trend of increasing frac demand is not forecast to continue as it is estimated that the demand will remain between 6,850,000 and 7,000,000 bbls/day through 2030. However, the PW volumes are anticipated to continue to increase over this period from 15,840,000 bbls/day to 24,050,000 bbls/day, thus out pacing demand by approximately another 10% to exceed demand by ~70% in 2030. The recycling capacity in 2022 was ~1,915,000 bbls/day reflecting a greater than 7.5-fold increase from the 2017 capacity of only ~250,000 bbls/day. This recycling capability

[67] Robert Crain, EVP, Texas Pacific Water Resources, Presentation – slide 2, HB 3516: New Rules for Commercial Recycling Facilities, Produced Water Society – August 2022 Conference, Midland, TX, Data Source, B3 Insight

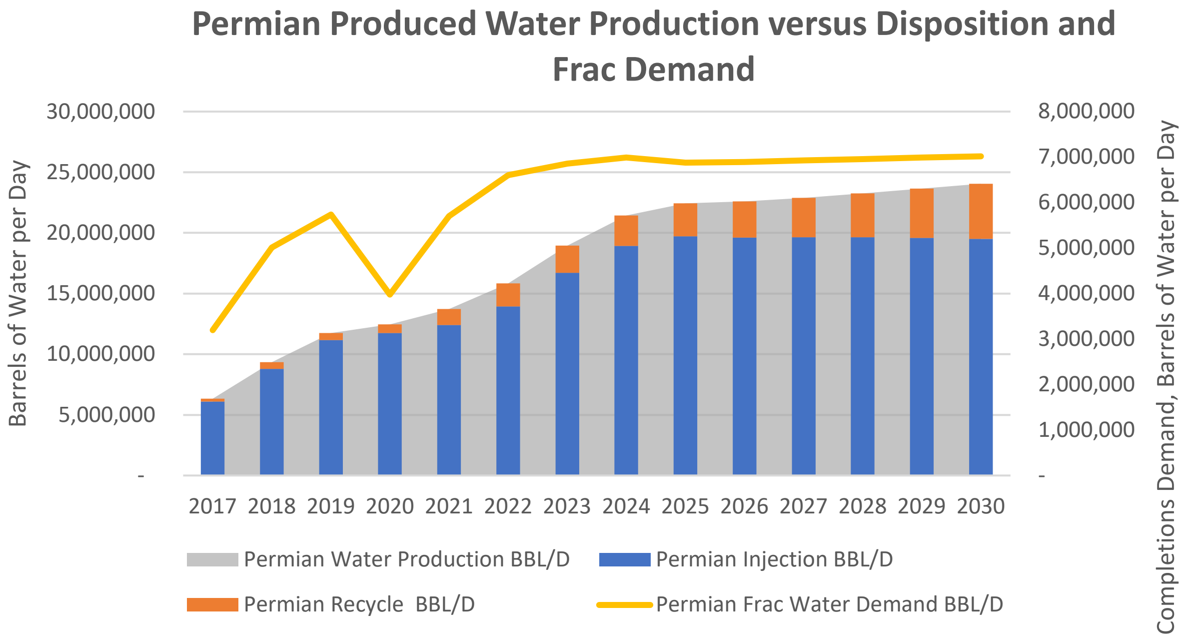

Figure 20: Permian Produced Water Production versus Disposition and Frac Demand[68]

is forecast to continue to grow at an exponential rate reaching roughly 4,550,000 bbls/day by 2030, resulting in an additional 10.5-fold increase over the 2017 capacity or approximately 2.4 times larger than the 2022 daily average volume. This forecast recycle capability will be able to deliver roughly 65% of the frac demand in 2030. The injection capacity in 2022 stands at nearly 24,000,000 bbls/day exceeding the PW volume by ~43% or ~10,000,000 bbls/day. This injection capacity is not forecast to grow over the next eight years but remains stagnant at 24M bbls/day capacity resulting in a 100,000 bbl/day shortfall by 2030. However, the injection capacity coupled with the recycling capability will exceed the PW volume for the foreseeable future.

The next two bar charts in **Figures 21 and 22** represent the Permian's daily injection volumes per annum from 2017 through 2030 versus the overall daily disposal capacities available regionwide. The graph in **Figure 21** demonstrates the daily Operational Disposal Capacity exceeds the Daily Injection Volume for the period evaluated (2017 – 2030) and a prospective sufficiency to handle the PW volume until 2030 when the PW volume is anticipated to exceed the disposal capacity by 97,400 bbls/day. Until then, the Permian Basin demonstrates an overall unused disposal capacity being available over the next 8 years that is estimated to be on average ~4.25M bbls/day. **Figure 22** illustrates the Permian Basin's PW injection rate versus the disposal capacity with the production volumes as estimated through year 2030.

[68] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

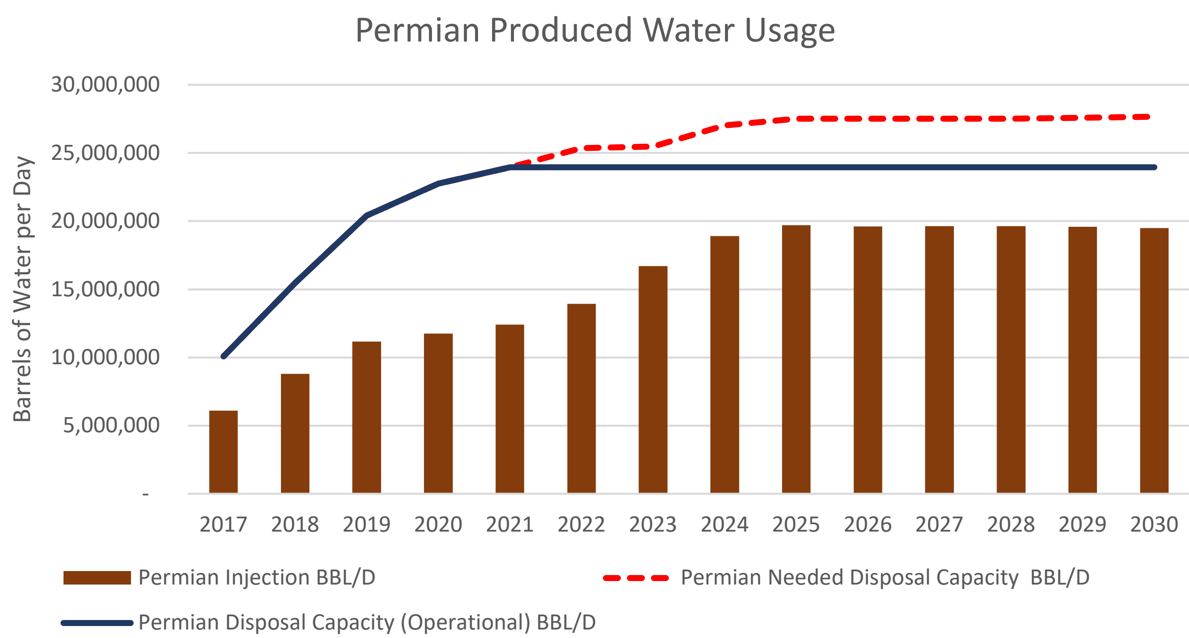

Figure 21: Permian Produced Water Usage[69]

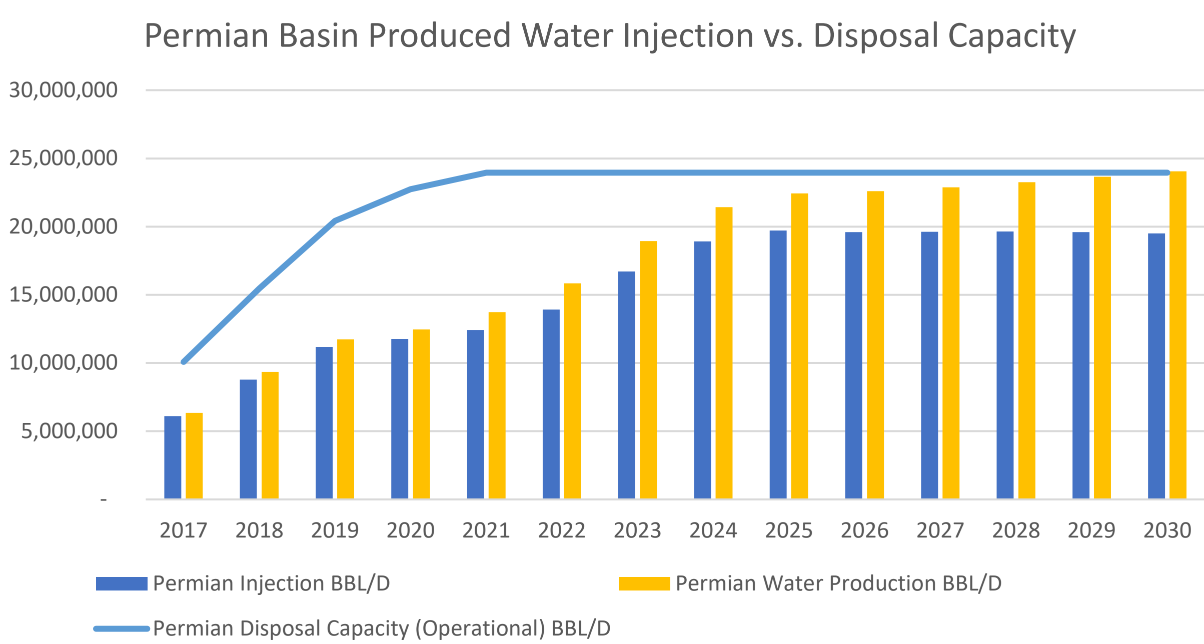

Figure 22: Permian Basin Produced Water Injection versus Disposal Capacity[70]

[69] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

[70] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

The bar chart in **Figure 23** depicts the scenario for the Permian meeting the daily frac demand with 100% recycled water as compared to the amount of water produced daily. The stacked bar also shows the portion of water remaining to be disposed of after the recycling water amount has been subtracted from the PW total. In other words, the charts are showing the change from before and after 2022 provided the future frac demand is met through recycling and thus reducing the amount of needed injection. As indicated, the Permian Basin produces far more water than frac-ing demands. The 100% recycling scenario to meet frac demand would triple the industry in 2023 from ~2.2M bbls/day to 6.8M bbls/day, however, the projected growth in recycling by 2030 would only represent a 35% increase that year as the industry would be at ~4.5Mbbls/day compared to the demand of 7.0M bbls/day. Also, the current disposal capacity of ~24.0 M bbls/day would be sufficient to support the industry through 2030, however, the current injection level of ~14.0M/bbls would decrease somewhat over the next 8 years averaging ~12.5M bbls/day.

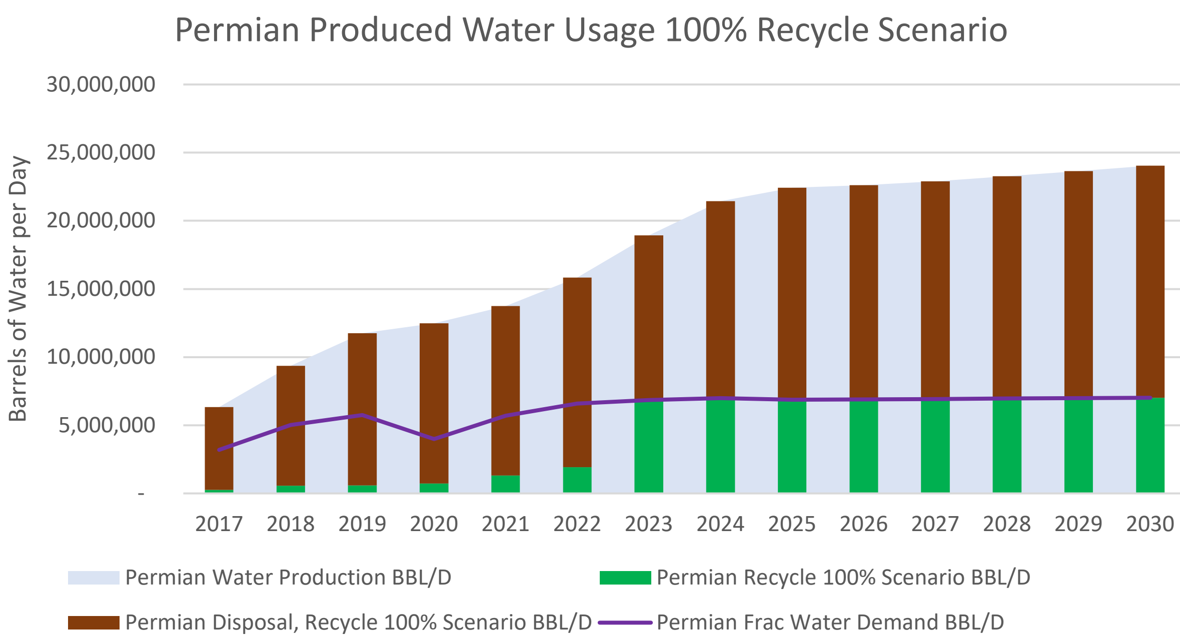

Figure 23: Permian Produced Water Usage 100% Recycle Scenario[71]

[71] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

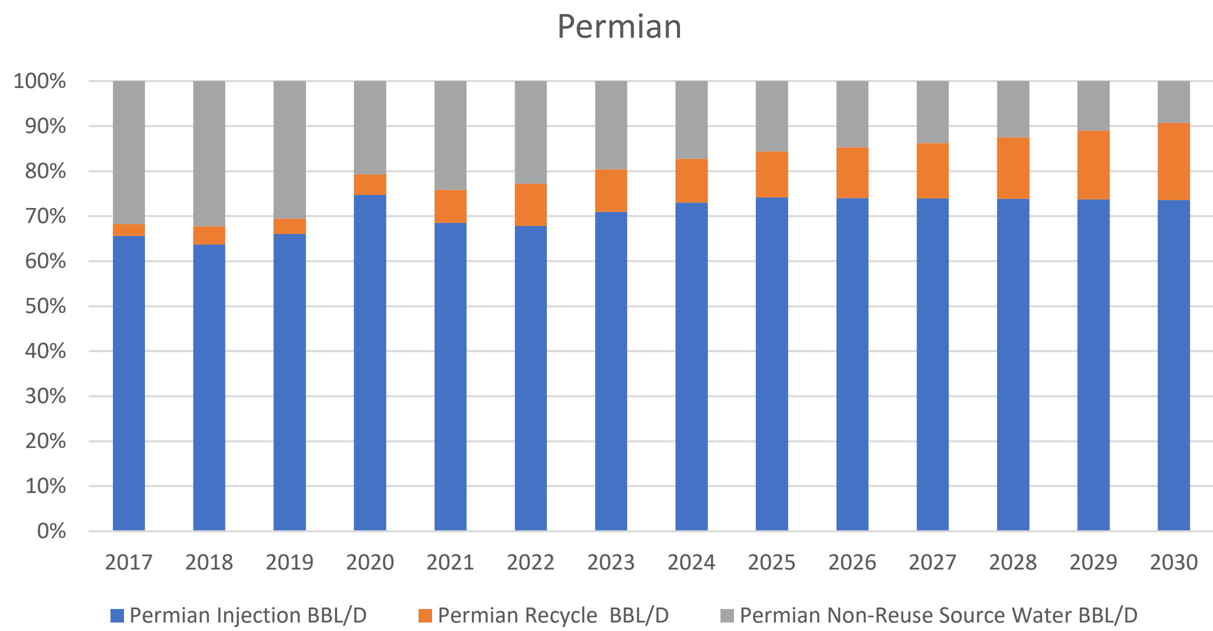

Figure 24: Permian Basin Available Volumes of Non-Reuse Source Water and Recycled Water[72]

The bar chart in **Figure 24** depicts the Permian Basin volumes of Non-Reuse Source Water and Recycled Water available for fracking, as well as the amount of water being Injected in bbls/day per annum as stacked bars, so the individual percentages of each use category can be compared. As demonstrated above, injection volumes dominate the water usage in the Permian with over 19M bbls/day (73%). The frac demand will be supplied roughly equally by Non-reuse Source water at 3.7M bbls/day and Recycled Water at 3.25M bbls/day. This combined total volume for fracking represents ~26% of the water usage in the basin on a daily basis.

3.1.2 Permian – Representative PW Operational and Management Framework

3.1.2.1 Operational Challenges (Permian Development Region)

High water cuts, and increased completions activity combined with existing water production have resulted in significant PW volumes and presented unique challenges across the water management arena. The scope of required infrastructure and associated capital expenditures resulted in the formation of a burgeoning mid-stream water sector that has grown significantly over the last five years. The midstream water sector has already experienced some market consolidation, and that is expected to increase as water networks grow and positively impact the PW management market. It should be noted that based on current data, current completions water usage accounts for +/- 30% of daily water production. Further challenges that must be addressed include seismicity when disposing of water in SWDs, formation pressure increases, and storage to facilitate larger buffer volumes to meet the need for water use surges that often occur during activities as indicated in **Figure 25**.

[72] ibid

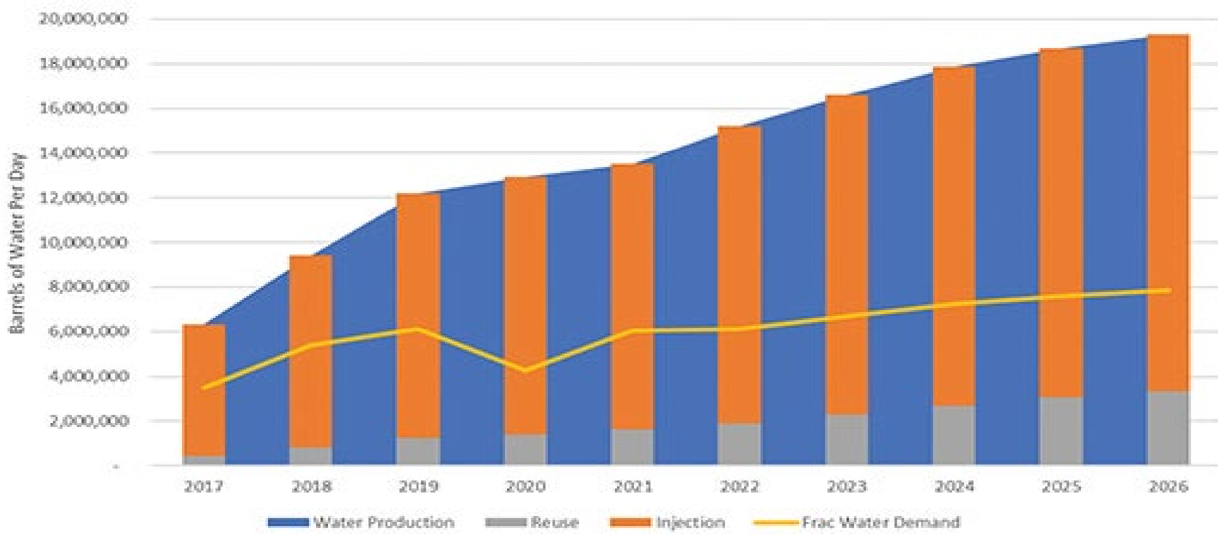

Figure 25: Historic and Future Projections for Permian Basin PW Use Surges [73]

This reuse has reduced reliance on limited fresh water resources significantly but estimates that reuse accounts for only 30% of water used in completions.

Approaches to mitigate the overall disposal volume of PW currently revolves around storage and reuse for completions. The volumes of PW that are being recycled for the next frac continue to increase, while the ability to have a large amount of water available for high-volume fracs necessitates additional storage capacity. It is expected that the continued transition of PW to be managed by third-party commercial water midstream companies will continue to grow as increasing PW volumes will necessitate future disposal. As this continues, the industry and regulatory community drive towards beneficial reuse.

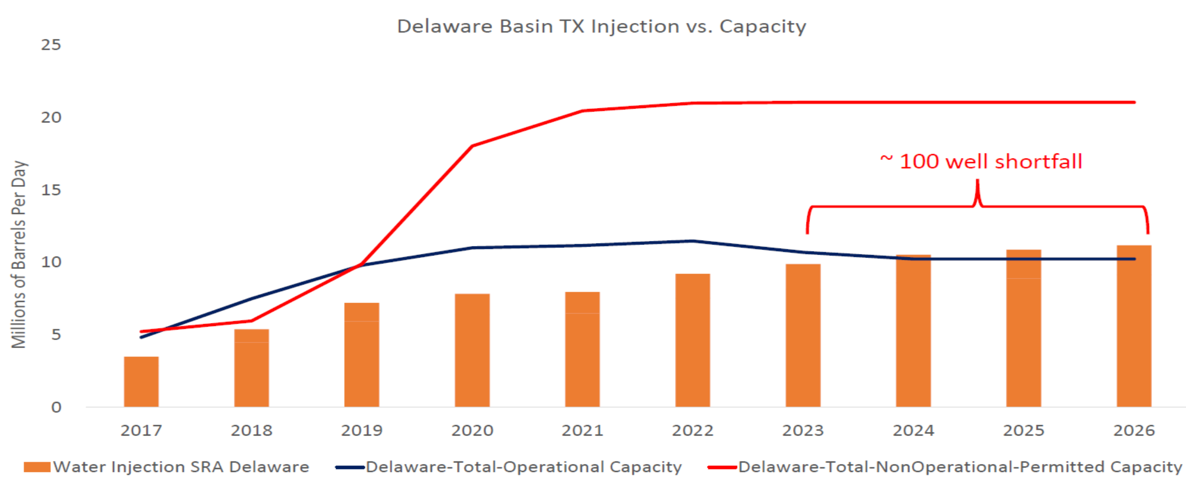

Figure 26: Delaware Basin Injection Rate versus Disposal Capacity [74]

[73] K. Wright, P. Patton, K. Bennett B3 Insight, The great saltwater flood in the Permian Basin, World Oil, https://www.worldoil.com/magazine/2022/july-2022/special-focus-permian-basin-technology-shale-technology/the-great-saltwater-flood-in-the-permian-basin/, accessed October 2022

[74] Oilfield Water Connection Marcellus Shale Water Business Update Conference, Marcellus-Utica Produced Water Trends [Data Keynote], Kelly Bennett, Co-Founder and CEO, B3 Insight, June 29, 2022

The graph in **Figure 26** shows that beginning in 2023, it is estimated that an additional 2.5 MM bbls/day of disposal capacity will be needed in the Delaware Basin by 2026, based on the current forecast as shown. This is equal to roughly 100 new SWD wells and will require more than $400MM in capital expenditure.

3.1.2.2 Development of Pipelines to Transport Water for Disposal

Due to the rapid development of oil and gas production sources and the associated volumes of PW that must be managed, water conveyance pipelines have been developed at an accelerated pace. This continues to significantly reduce the volume of water trucked to SWD wells.

Many of these pipelines are fit-for-purpose pipelines that are owned, operative, and captive to a given operator or midstream company, and not interconnected with other pipelines within the same region. However, since the Seismic Response Area (SRA) has caused abrupt changes in the management of disposal volumes, as a matter of necessity there is growing cooperation between water midstream companies to share pipeline capacity to help in moving and managing water out of these contentious areas. **Figure 27 s**hows the volume of PW trucked quarterly in the Midland and Delaware basins from 2017 through 2021.

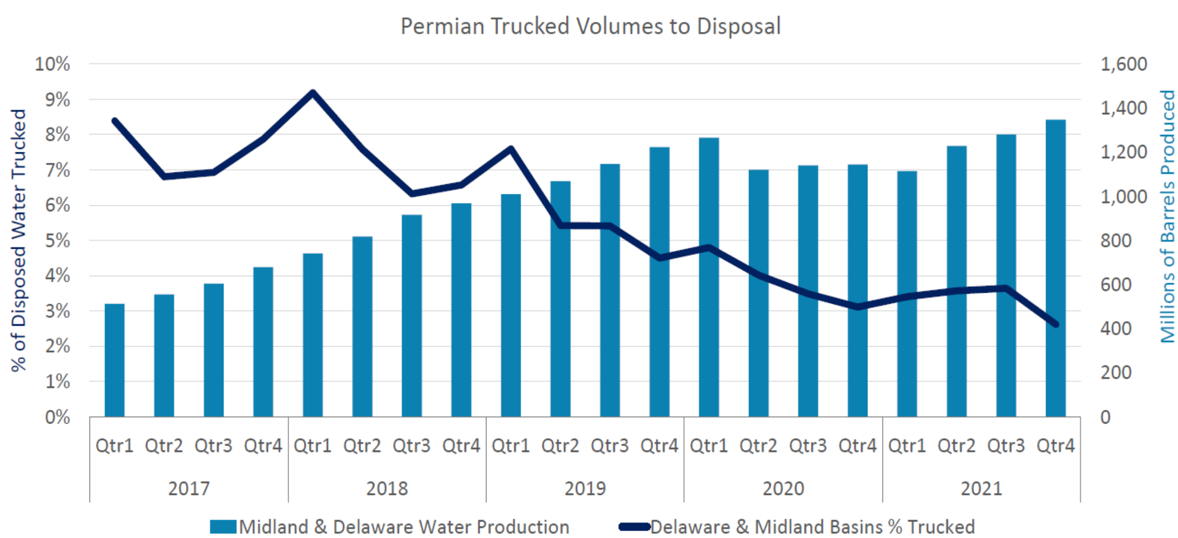

Figure 27: Permian Trucked Volumes to Disposal[75]

3.1.2.3 Water Treatment Targets for Recycling in the Permian Development Region

When water is not disposed of in SWD wells, it is recycled for reuse within the oilfield to support completion activities. When recycled in this fashion, water is often treated to some quality specification required by the operator. Even though there is no industry-wide treatment standard for PW recycled in the Permian Basin Development Region, all information indicates that a common treatment specification is forming. It is common practice for midstream water companies to return water to operators for their next completion, requiring water to meet a minimum specification that typically falls

[75] Oilfield Water Connection Marcellus Shale Water Business Update Conference, Marcellus-Utica Produced Water Trends [Data Keynote], Kelly Bennett, Co-Founder and CEO, B3 Insight, June 29, 2022

into one of three treatment ranges. **Figure 28** depicts the typical high, mid, and low specification (spec) treatment standards offered.

		High-Spec Treatment	Mid-Spec Treatment	Low-Spec Treatment
TOG	*mg/L*	< 10	< 30	< 100
TSS	*mg/L*	< 50	< 200	< 1,000
Total Fe	*mg/L*	< 5	< 10	n/a
H_2S	*mg/L*	*ND*	*ND*	*ND*
ORP	*mv*	> 300	> 150	> 0
pH	*n/a*	6-8	6-8	6-8
Bacteria/ ATP	*pg/ml*	< 50	< 100	< 500
Typical processes		• Oil/water separation • Aggressive oxidation • Filtration and/or flocculation	• Oil/water separation • Mild oxidation • Solid settlement	• Oil/water separation • Minimum oxidation • Specific process tailored to the needs

Legend: TOG – Total Oil and Grease, TSS – Total Suspended Solids, Total Fe- Total iron, H_2S -Hydrogen Sulfide, ORP – Oxidation-Reduction Potential (the ability to oxidize (or reduce) another substance), pH – (a measure of how acidic or basic a solution is), Bacteria / ATP - ATP stands for adenosine triphosphate, which is a substance found in all living things. By testing for ATP, the presence and number of bacteria in a given sample are determined.

Figure 28: Typical High-, Mid-, and Low Specification Treatment Standards[76]

Each completion manager has an expectation of the minimal water quality requirements should water be used from one frac to the next without storage. However, one of the main drivers for the level of treatment required has an interdependent relationship with the length of time PW is expected to be stored prior to being recycled for the next frac. If water is to be stored for longer than a day, water must have low levels of solids and hydrocarbons present and will have gone through some level of oxidation.

To facilitate the removal/reduction of Total Oil and Grease (TOG), and Total Suspended Solids (TSS), many operators utilize a technology called Dissolved Air Flotation (DAF), which is a water treatment process that clarifies water by removing solids and/or oil out of suspension, by introducing small air bubbles in the water. These bubbles adhere to suspended matter in the water, causing it to float to the surface where it can easily be removed, normally by skimming the surface. In conjunction with this physical process, coagulation and flocculation chemicals are often injected into the process to improve removal efficiency. During the treatment process, the goal is to operate as close to a neutral pH as possible (pH from 6-8), in order to minimize the aggregation of solids and minimize the potential for Normally Occurring Radioactive Material (NORM). The liquid waste stream is often placed in a disposal well as a slurry, while it is common for the solids to be pressed into a filter cake, and disposed of at a landfill. A common size of a DAF unit used for this purpose can routinely handle somewhere in the range of 80,000 to 100,000+ bwpd.

[76] Select Energy Services, "Sustainability Outlook: Exploring the Potential of Produced Water in 2023" – Nov. 9, 2022, Presentation, Rick McCurdy, VP Sustainability, and Innovation (https://selectenergyses.wistia.com/medias/7vzwkk47xm¬)

To facilitate the removal/reduction of H_2S, Total Fe (Iron), and Bacteria, oxidation is accomplished by both physical and chemical means. These processes serve to convert dissolved iron to its solid form, making it easy for removal. In addition, oxidation eliminates H_2S from the water and serves to also reduce bacteria levels in the water. Measuring the Oxidation-Reduction Potential (ORP) after physical and/or chemical treatment is used to determine the oxidation efficacy. The 3 treatment specifications for oxidation and the technology used to commonly achieve the targeted treatment goal are as follows:

- **Minimum Oxidation:** Oxidative chemicals such as hydrogen peroxide, bleach (sodium hypochlorite), or ozone, are injected and mixed into the PW. These chemicals convert dissolved (ferrous) iron into solid (ferric) iron, allowing the solid form to be easily removed from the water. The addition of these oxidizers serves as a biocide and creates a positive ORP state where the measured ORP > 0 mV). However, low ORP levels in treated PW typically dissipate within a few days when the water is stored in a storage pond or impoundment without any additional oxidative steps taken. In terms of practical application, ORP minimum oxidation is applicable if the PW is to be recycled for an upcoming frac in an expedient manner.
- **Medium Oxidation** – During the initial phases of the treatment process, additional chemical is added to bring the ORP to a level >150mV. By doing so, in addition to the benefits described above with Minimum Oxidation, once water is placed in a storage impoundment it is continually aerated to help maintain the positive ORP state after the initial chemical reaction. Unfortunately, this residual level of ORP leaves a minimal cushion to maintain a positive state. When water at this level of ORP is placed into impoundments with aeration systems that are undersized or not maintained properly, makes it difficult to maintain water in a positive ORP state.
- **Aggressive Oxidation** – During the initial phases of the treatment process, the PW is treated with a combination of different oxidative chemicals (or an aggressive dose of one oxidizer) to drive the ORP value above 300 mV. When combined with an adequately sized and maintained aeration system at an impoundment, the ORP retains its positive state. It should be noted that higher levels of ORP >300mV) are most desired if water is going into a storage pit or impoundment for storage to help ensure the water does not become septic. However, water with high levels of ORP increases chemical costs for treatment and has been known to impede friction reducer (FR) in frac jobs.

3.1.2.4 TX HB-3516 and Why Changes to H-11 Process Were Needed

As mentioned at the beginning of this section, the goals of original PW recycling rules in Texas were well-intentioned and resulted in significant operator-based recycling efforts. These rules resulted in a streamlined ability for leaseholders (i.e., operators of record) to recycle water for upcoming completion operations in the form of a “Non-Commercial Fluid Recycling Pit Permit.” Alternatively, the commercial recycling permitting process significantly hampered commercial recycling efforts due to cumbersome and un-timely processes/approvals often taking up to a year plus for approval. Market conditions for PW in the Permian Basin necessitated changes to the commercial recycling process in order to streamline permitting efforts by third-party water mid-stream companies. PW has transitioned from a waste product destined primarily for downhole disposal, to a commodity to be used for upcoming completions, EOR, or beneficial reuse.

This challenge for commercial operations was compounded by high-intensity simul-frac design combined with high water-cut demands and the need for excess high-volume storage. In order to facilitate these demands, water mid-stream companies required exacting concise permitting/construction guidelines and timeframes for permitting that were compounded by the challenge of ever-evolving drilling plans. The promise of HB 3516 is to improve the permitting and construction process to alleviate these challenges.

Industry leaders felt that the rules adopted under this section for commercial recycling of fluid oil and water as waste must establish:

- Minimum siting standards for fluid recycling pits to provide clarity in order to exclude non-conforming sites.
- Uniform technical, construction, and placement standards, with detailed specifications regarding guidelines to expedite the permitting process, with a promise of expedited and known permit approval timeframes.
- Uniform standards for estimating closure costs and eliminating the ambiguity regarding closure cost estimating procedures.
- Minimum and maximum bonding and financial security amounts based on factors determined by the commission that establish financial parameters sufficient to protect landowners and RRC regarding bonding amounts.
- Standards for sampling and analysis of oil and gas wastes while providing uniform analytical and sampling guidelines.
- A short duration (i.e., 90-day) approval process assuming permit conditions are met with no protests or variances requested.

It is understood that the next steps will involve the RRC drafting rules in 2022/23 with implementation to follow shortly thereafter.

3.2 Eagle Ford Development – Produced Water Market Profile and Analysis

The bar chart in **Figure 29** depicts and projects the daily volume of PW in barrels per annum in the Eagle Ford Development Region from 2017 through 2030. This daily volume is then compared to the daily injection volume and recycle quantities available or forecasted per year. Finally, the demand for water to be used for fracking operations is graphed in bbls/day as well, indicating either a shortfall or an abundance of recycled water available to meet this demand.

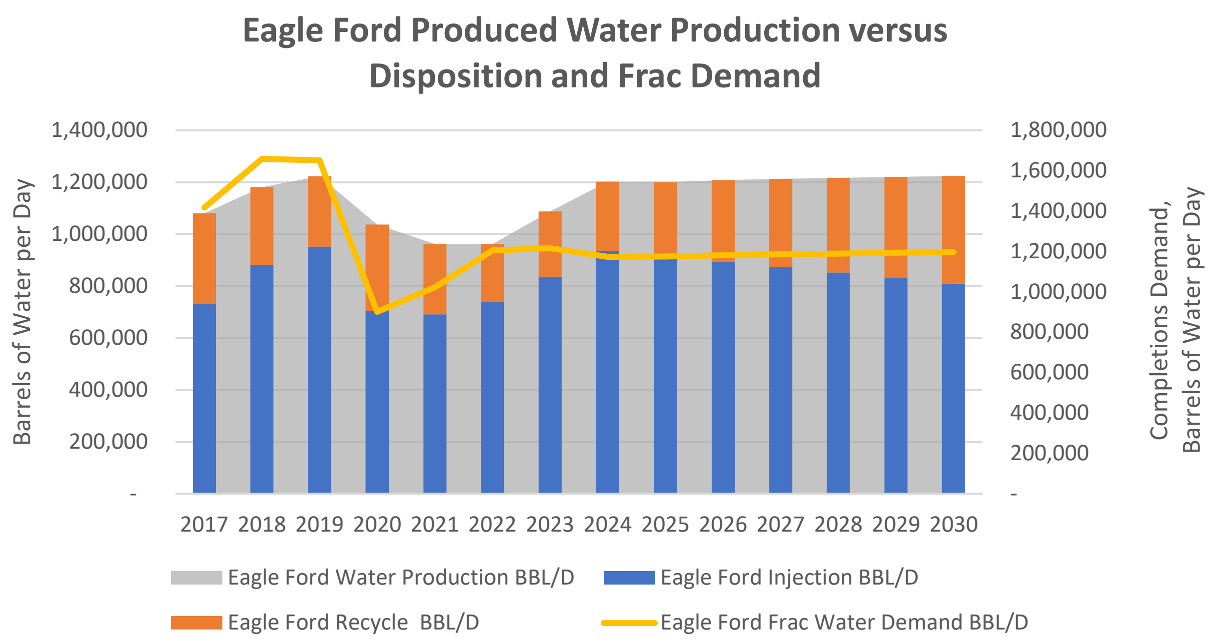

Figure 29: Eagle Ford Produced Water Production versus Disposition and Frac Demand[77]

This basin was short by an average of 225,000 bbls/day of generating enough PW to meet the frac demand during the period of 2017 through 2022 but appears to be reaching a rough equilibrium for the forecasted time frame of 2023 through 2030. The predicted average daily production versus demand for this period is 1,197,000 bbls vs. 1,189,000 bbls. The current recycled volume is trending at about 225,000 bbls/day but is projected to increase by nearly 100% to 415,000 bbls/day by 2030. This recycled volume however will still only represent approximately 35% of the daily frac demand in 2030. The injection capacity is currently estimated at 1,650,000 bbls/day and is predicted to remain at this level through 2030, thus providing approximately 25% excess capacity versus the volume of PW anticipated over this period.

The next two bar charts in **Figures 30 and 31** represent the Eagle Ford Development Region's daily injection volumes per annum from 2017 through 2030 versus the overall daily disposal capacities available regionwide. This data demonstrates that this region has sufficient regional disposal capacity for the estimated PW volume over the next 8 years and shows an unused disposal capacity of >700,000 bbls/day on average.

[77] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

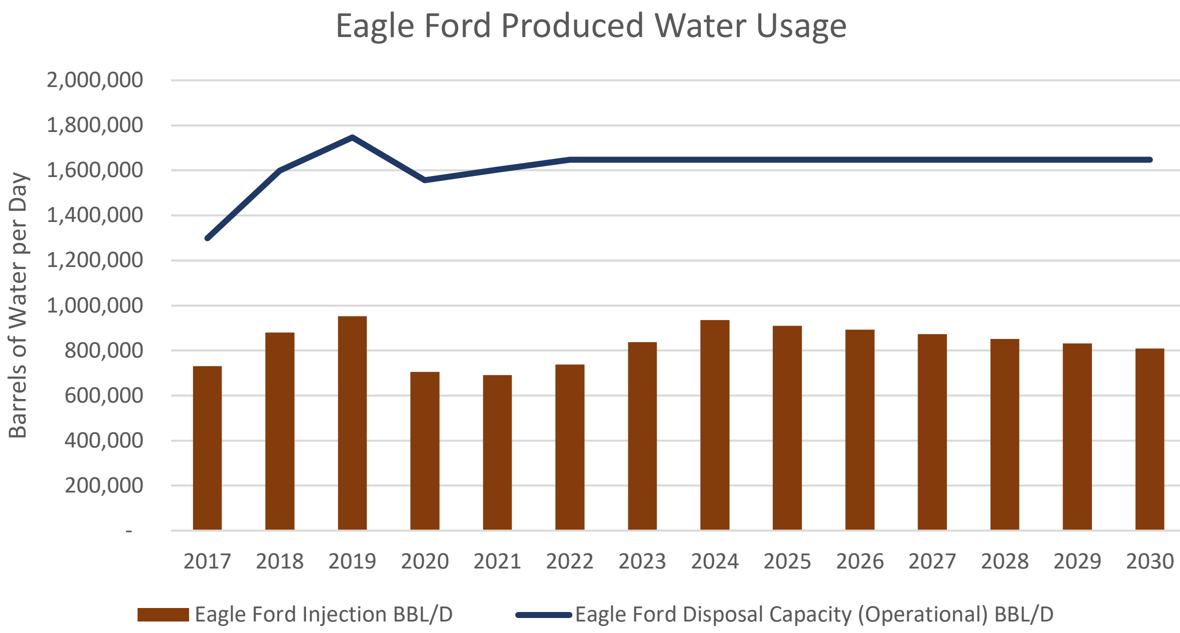

Figure 30: Eagle Ford Produced Water Usage[78]

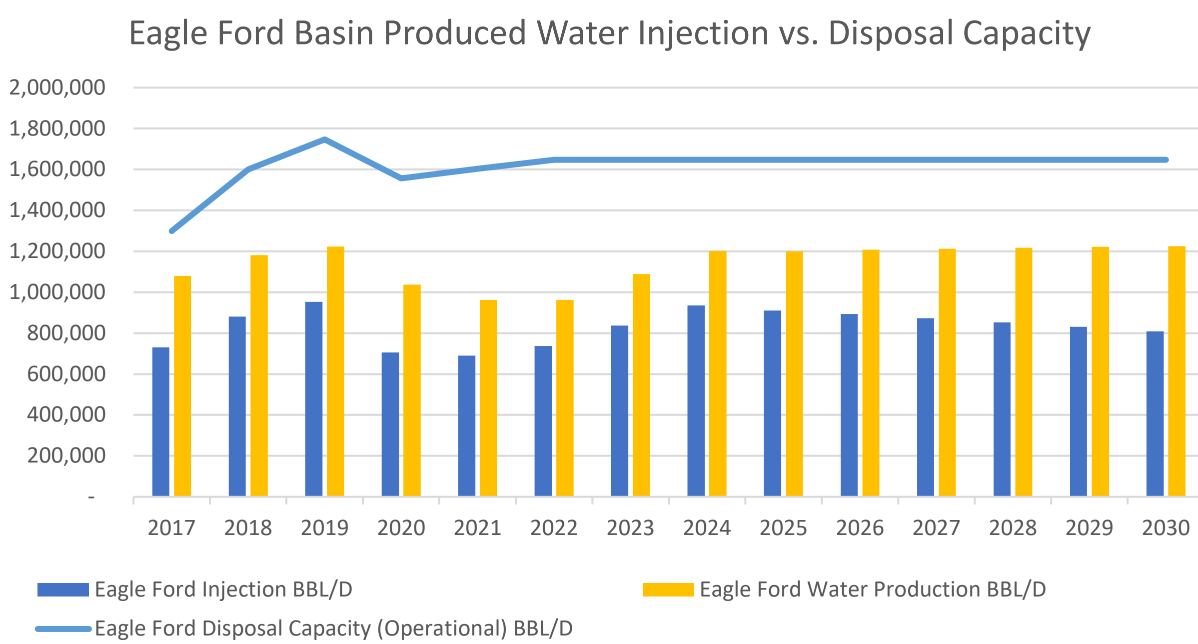

Figure 31: Eagle Ford Basin Produced Water Injection versus Disposal Capacity[79]

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[78] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

[79] ibid

The bar chart in **Figure 32** for the Eagle Ford depicts the scenario of meeting the daily frac demand with 100% recycled water as compared to the amount of PW produced daily. The stacked bar also shows the portion of water remaining to be disposed of after the recycling water amount has been subtracted from the PW total. In other words, the charts are showing the change from before and after 2022 provided the future frac demand is met through recycling and thus reducing the amount of needed injection. In this region, if 100% of the frac demand was met via recycling, then nearly all the PW would need to be diverted for recycling while only about 30,000 bbls/day would need to be disposed of through injection. This would reduce the projected injection volumes by nearly 850,000 bbls/day.

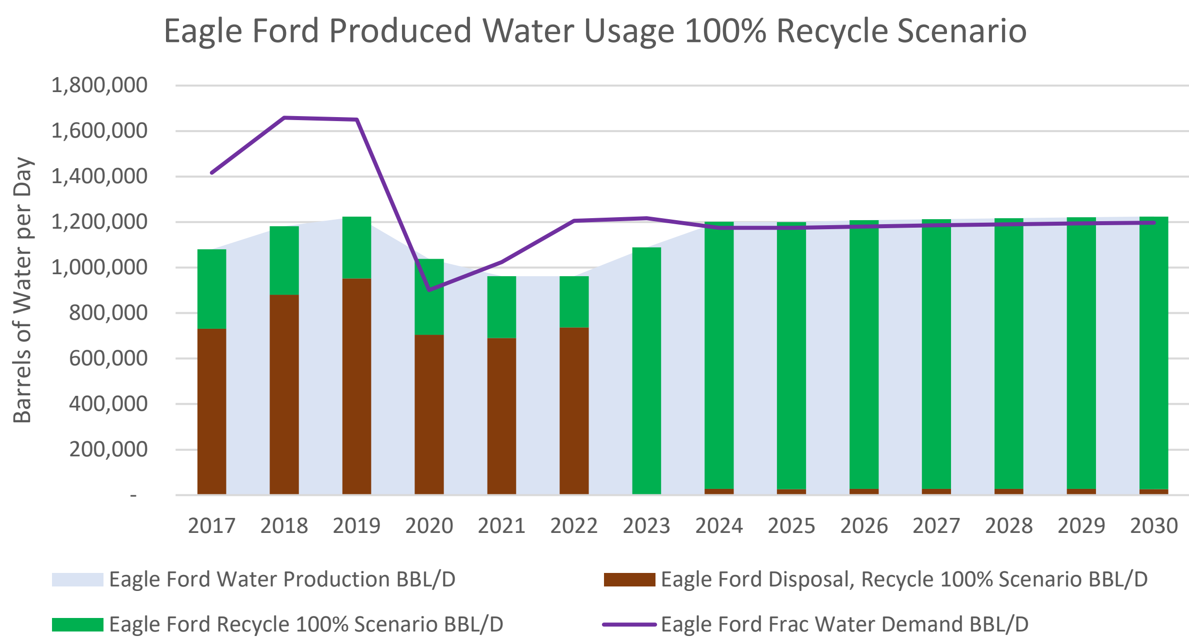

Figure 32: Eagle Ford Produced Water Usage 100% Recycle Scenario[80]

Figure 33 shows a bar chart that depicts the Eagle Ford Region Non-Reuse Source Water and Recycled Water volumes available for fracking, as well as the amount of water being Injected in bbls/day per annum. The stacked bars show the individual percentages of each use category. As demonstrated, the South TX / Eagle Ford water usage is somewhat more level with Injection projected to account for an average of 865,000 bbls/day or ~40% of the combined volumes over the future 8-year period, whereas Non-reuse Source Water also represents ~40% (~860,000 bbls/day), thus recycled water provides the remaining ~20% or (330,000 bbls/day).

[80] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

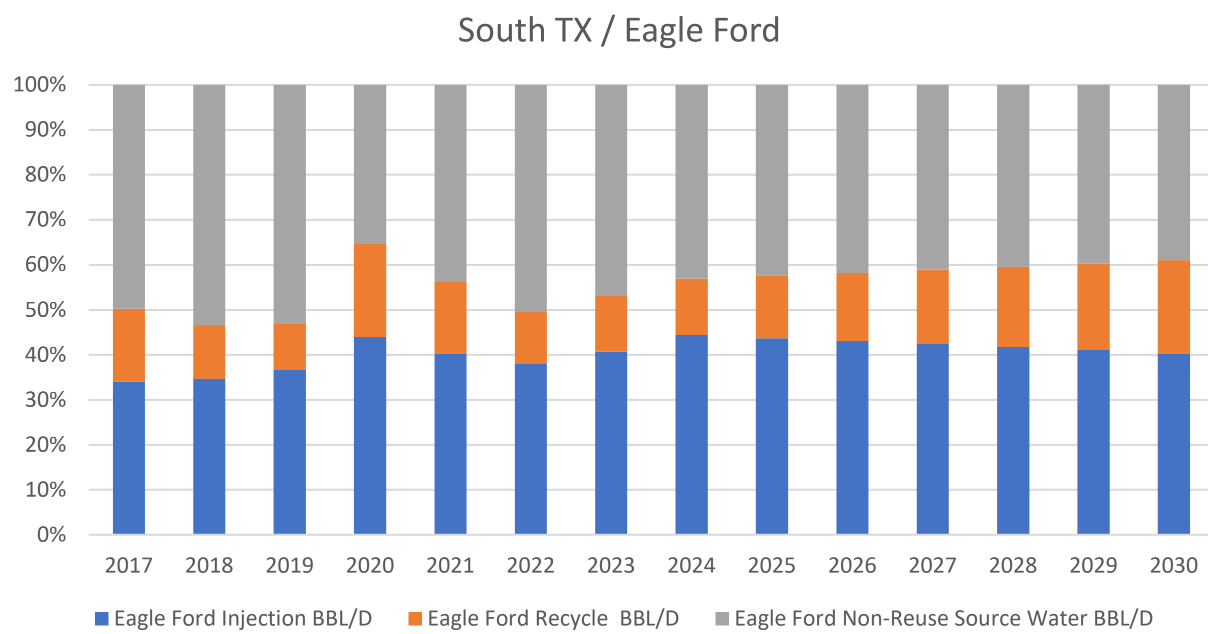

Figure 33: Eagle Ford Non-Reuse Source Water and Recycled Water Available for Fracking[81]

The amount of reuse in the Eagle Ford is currently very limited. There are several contributing factors but generally, this is because water production significantly drops following the initial flowback stage. The other contributing factors include surface lease agreements that require operators to pull fresh water from the surface landowners, existing networks of pipelines that send PW directly to disposal wells, and fracking is routinely accomplished with brackish water as the Carrizo-Wilcox Aquifer and surrounding minor aquifers below the primary recharge zone are of a brackish nature approaching upwards of 1,000 ppm TDS.

3.3 Appalachian Development – Produced Water Market Profile and Analysis

The number of wells completed by state within the Appalachian Basin from 2011 through 2021 is graphically illustrated in **Figure 34**. The graph indicates that Pennsylvania is outpacing the other four states (Kentucky, Ohio, Virginia, West Virginia) combined in drilling and completing wells over this period with an average of nearly 1,000 wells per year in the first 5-year period followed by 500 wells/year over the second half-decade.

The wells completed versus the total base frac water volume used as reported via FracFocus for the Appalachian Development Region over the same 2011- 2021 period is presented in **Figure 35**. The total base frac water used has increased over the decade from roughly 50 Mbbls/well in 2011 to over 400Mbbls/well by 2021. The number of completions reported saw an increase over the first four years to a high of ~2,000/year, but declined over the proceeding six years to ~800/year in 2021.

[81] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

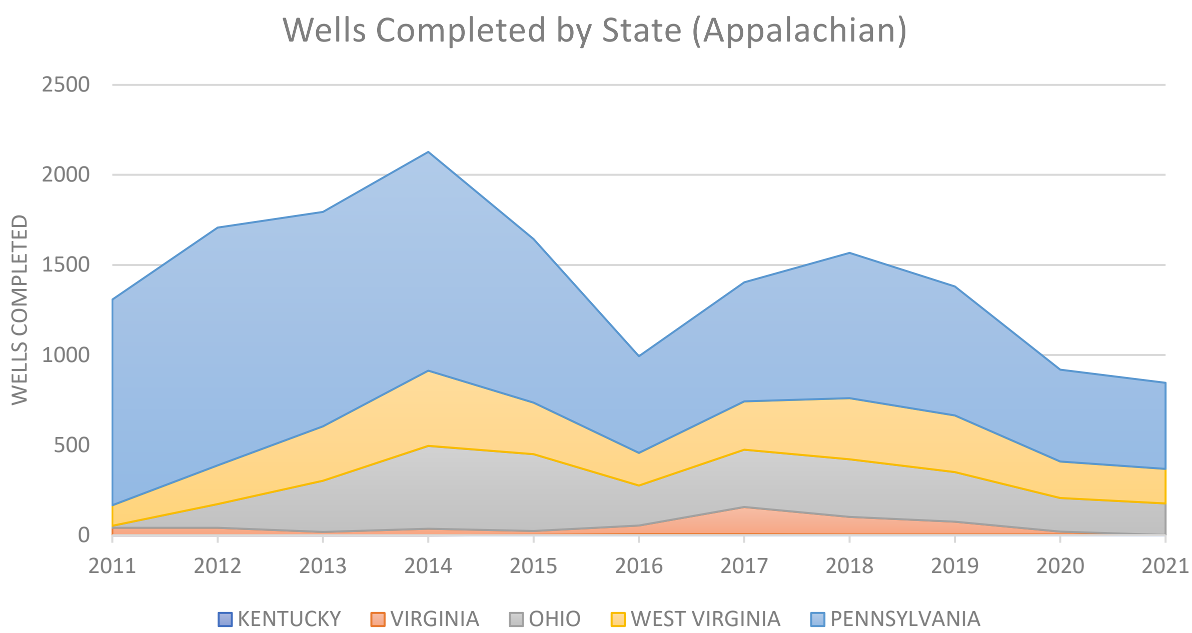

Figure 34: Wells Completed by State Appalachian Basin[82]

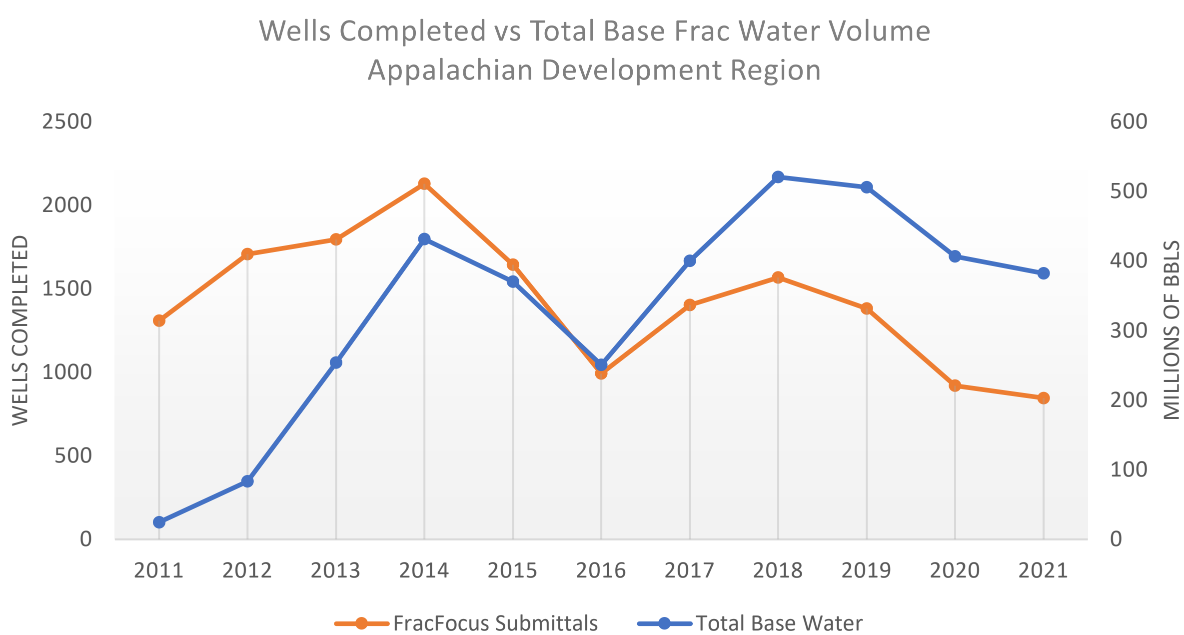

Figure 35: Wells Competed versus Total Base Frac Water Volume Appalachian Development Region[83]

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[82] ALL Consulting work product, Data source: FracFocus Chemical Disclosure Registry, Data Download SQL Data, analyzed accordingly, August 2022.

[83] ALL Consulting work product, Data source: FracFocus Chemical Disclosure Registry, Data Download SQL Data, analyzed accordingly, August 2022.

The bar chart In **Figure 36** depicts and projects the daily volume of PW in barrels per annum in the Appalachian Development Region from 2017 through 2030. This daily volume is then compared to the daily injection volume and recycle quantities available or forecasted per year. Finally, the demand for water to be used for fracking operations is graphed in bbls/day as well, indicating either a shortfall or an abundance of recycled water available to meet this demand.

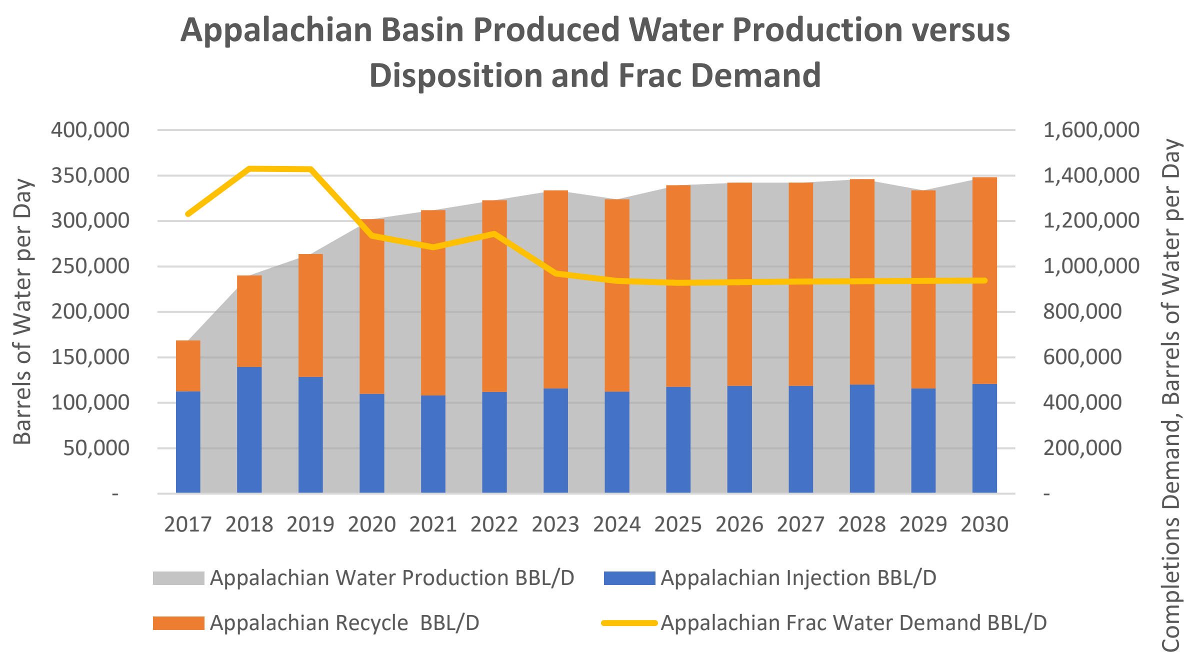

Figure 36: Wells Completed by State Appalachian Basin[84]

This basin did not produce sufficient volumes of PW to meet the frac demand between 2017 and 2022 nor is it anticipated to generate enough PW for the projected frac demand through 2030; the shortfall is calculated to be ~64% daily per annum over this eight-year period, (e.g., average daily PW volume of 338,500 bbls versus an average daily frac demand of 938,000 bbls). The average amount of water being recycled is roughly 210,000 bbls/day for this initial period and is not expected to increase rapidly over the next 8-year time frame. This recycled volume however coupled with the available average injection capacity (~150,000 bbls/day) appears sufficient to manage the current and projected produced volumes.

The bar charts in **Figures 37 and 38** represent the Appalachian Regional Development Area's daily injection volumes per annum from 2017 through 2030 versus the overall daily disposal capacities available regionwide. This graph shows that this basin does not and will not have sufficient disposal capacity to handle the projected PW volume, however, the charts reveal that there is approximately 40,000 bbls/day of unused disposal capacity on average through the remaining eight years, available for additional injection.

[84] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

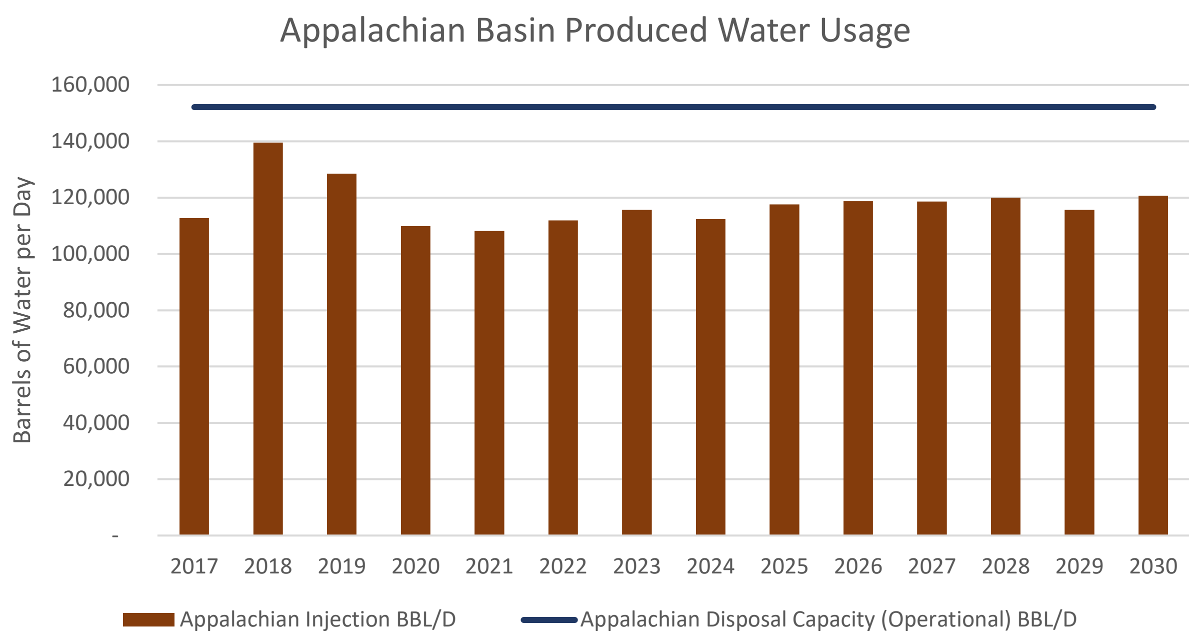

Figure 37: Appalachian Basin Produced Water Usage[85]

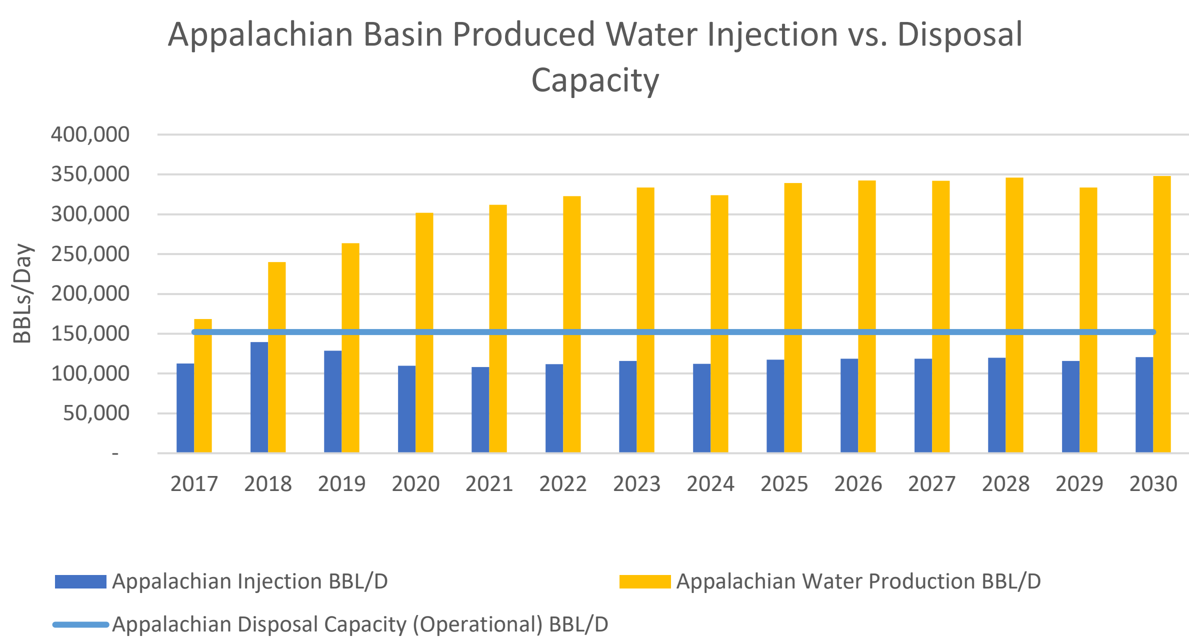

Figure 38: Appalachian Basin Produced Water Injection versus Disposal Capacity[86]

[85] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

[86] ibid

The scenario for the Appalachian Region meeting the daily frac demand with 100% recycled water as compared to the amount of water produced daily is presented in **Figure 39**. The stacked bar also shows the portion of water remaining to be disposed of after the recycling water amount has been subtracted from the PW total. In other words, the charts are showing the change from before and after 2022 provided the future frac demand is met through recycling and thus reducing the amount of needed injection. In this basin, it is apparent that if all the PW was recycled moving forward toward 2030, the frac demand would not be met, thus requiring the use of non-reuse source water to make up the difference. Roughly, 700,000 bbls/day of non-reuse source water would be needed to meet the frac demand through 2030.

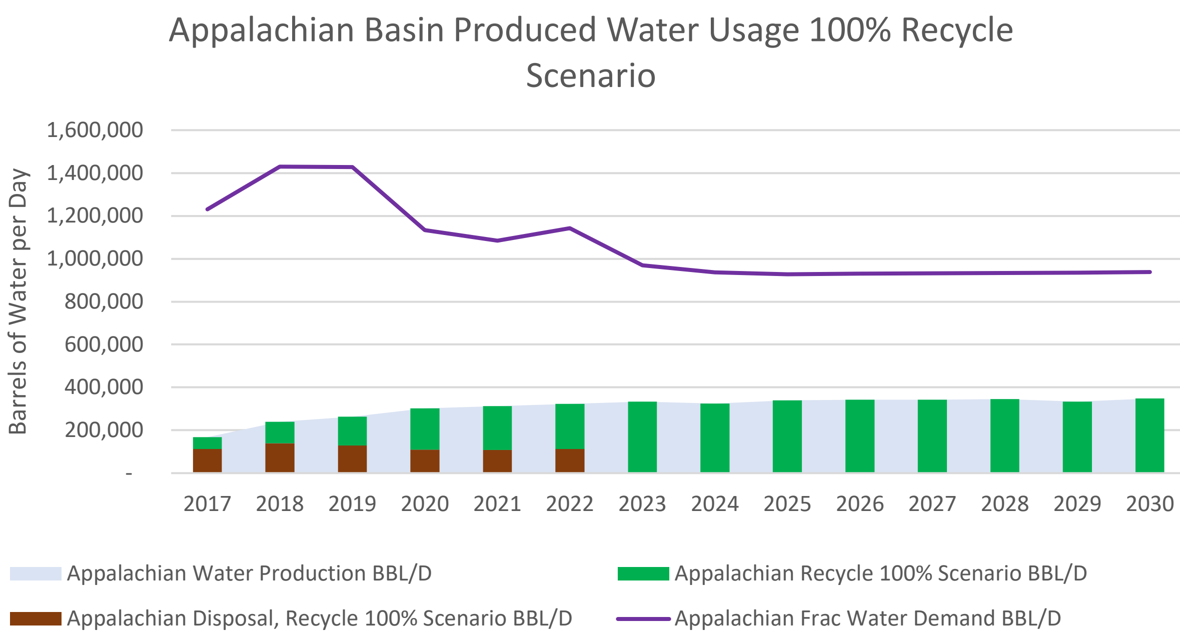

Figure 39: Appalachian Basin Produced Water Usage 100% Recycle Scenario[87]

Figure 40 shows the Appalachian Region's Non-Reuse Source Water and Recycled Water volumes available for fracking, as well as the amount of water being injected in bbls/day per annum. The stacked bars show the individual percentages of each use category. As demonstrated the water usage for completion activities will be primarily supplied by non-reuse source water (~700,000 bbls/day) with recycled water (~200,000 bbls/day) making up approximately a third of the demand moving forward from 2023 through 2030. Injection volume will remain rather stagnate over this period at roughly ~115,000 bbls/day or just over 10% of the frac demand.

PW as managed in Pennsylvania over the period of 2017 to 2022 is presented in **Figure 41**. This graph uses a stacked bar at 100 percent to illustrate the representative operational framework for the management of PW. It becomes obvious that operators are recycling as much water as possible due to the proximity of disposal wells. Particularly in the northeast corner of Pennsylvania as operators are reusing the PW or paying another operator to reuse it. On the other hand, the southwest portion of

[87] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

Pennsylvania tries to reuse PW but has better access to disposal wells in Ohio and therefore accounts for the majority of exported PW. The current market constraints are being solved with disposal.

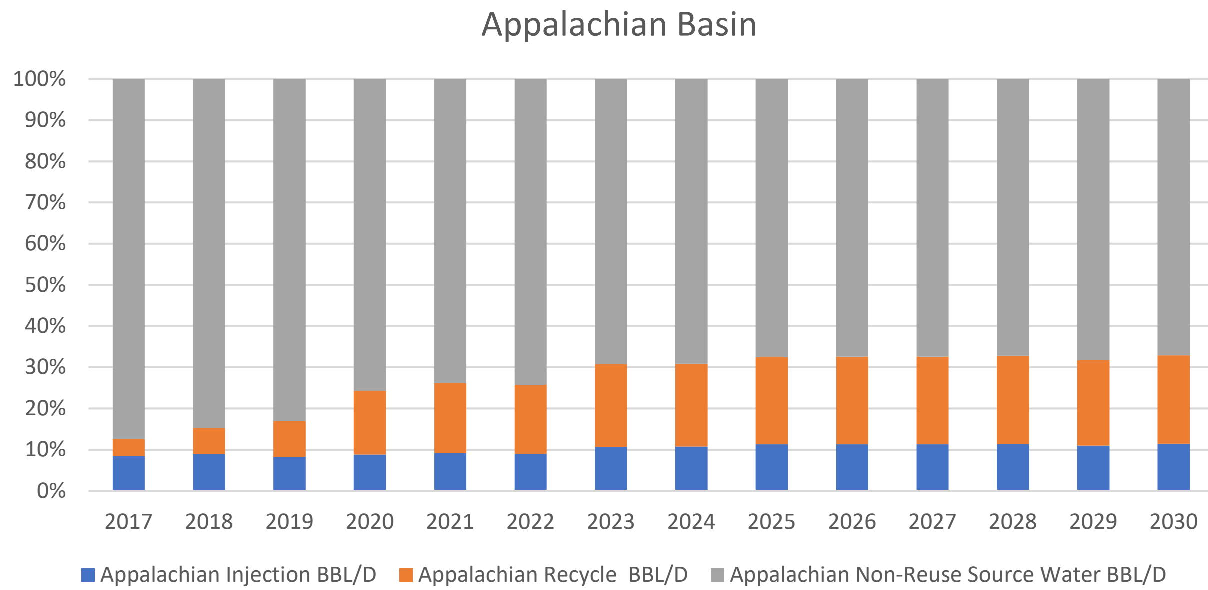

Figure 40: Available Non-Reuse Source Water and Recycled Water Volumes for Fracking[88]

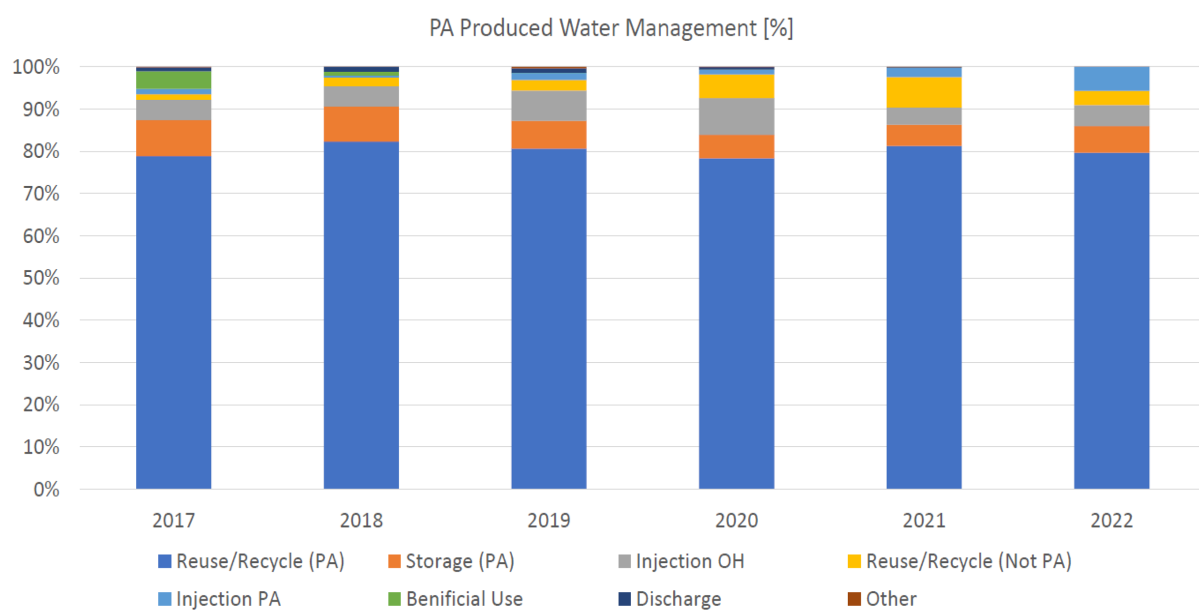

Figure 41: Pennsylvania Produced Water Management Percentages[89]

[88] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

[89] OWC Market Update – Marcellus, June 29, 2022 (focus on PA)

3.4 Bakken - Produced Water Market Profile and Analysis

As indicated by the original GWPC PW Report, the Bakken Development Region heavily relies on a large percentage of fresh water for completions with only a small percentage of PW being recycled for ongoing completion operations. PW in the Bakken has the highest level of mean TDS of all development water being recycled.

The bar chart in **Figure 42** depicts and projects the daily volume of PW in barrels per annum in the Bakken Development Region from 2017 through 2030. This daily volume is then compared to the daily injection volume and recycle quantities available or forecasted per year. Finally, the demand for water to be used for fracking operations is graphed in bbls/day as well, indicating either a shortfall or an abundance of recycled water available to meet this demand.

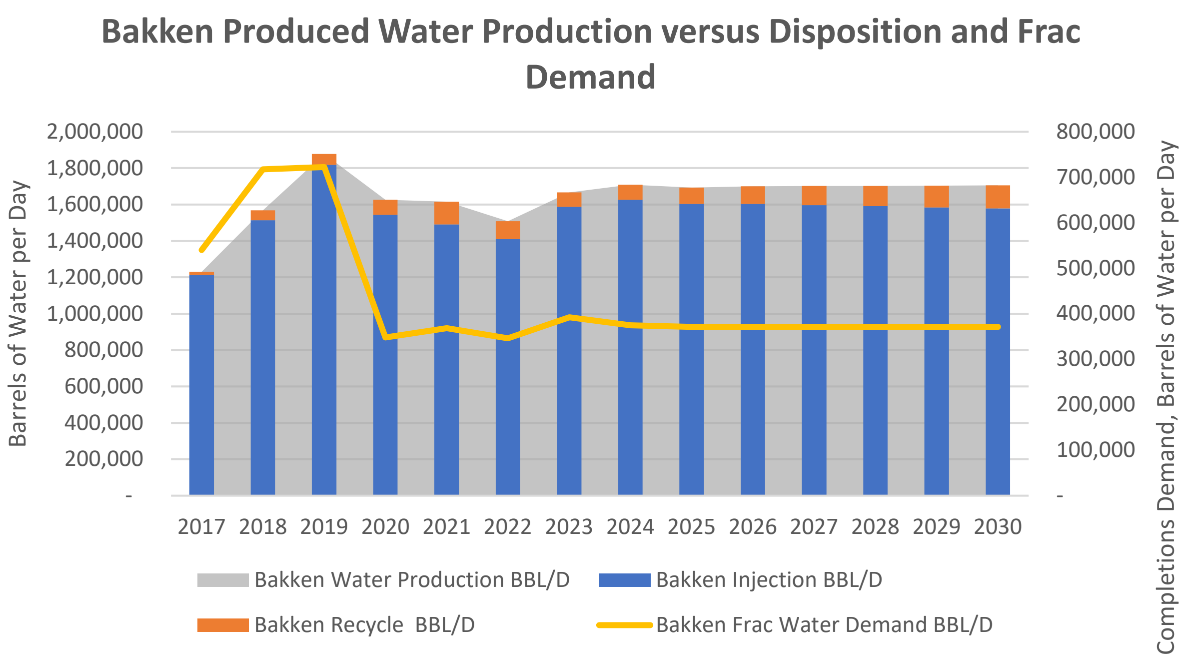

Figure 42: Bakken Produced Water Production versus Disposition and Frac Demand[90]

Bakken Basin supplied enough PW to meet the frac demand from 2017 through 2022 and is predicted to continue to produce excess quantities of PW versus the frac demand through 2030. The surplus volume of PW is calculated to be approximately 454% on a daily basis through 2030, (e.g., average daily PW volume of 1,698,000 bbls versus an average daily frac demand of 374,000 bbls). The daily volume being recycling is under 100,000 bbls/day and is projected to grow at a modest rate to ~125,000 bbls/day by 2030, thus it only fulfills approximately 33% of the anticipated frac demand. The injection capacity, on the other hand, far exceeds the production volume with a current 3,719,000 bbls /day and is forecasted to remain at this level through 2030. Hence, the injection capacity and recycling capabilities of the basin are more than sufficient to manage the predicted average daily PW volumes through the end of the decade.

[90] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

The two bar charts presented in **Figures 43 and 44** represent the Bakken's daily injection volumes per annum from 2017 through 2030 versus the overall daily disposal capacities available regionwide. These graphs demonstrate the Bakken Basin has sufficient disposal capacity for the estimated PW volume for the next 8 years, according to the charts it should have on average >2.0M bbls/day of unused disposal capacity as compared to its injection volume over this period.

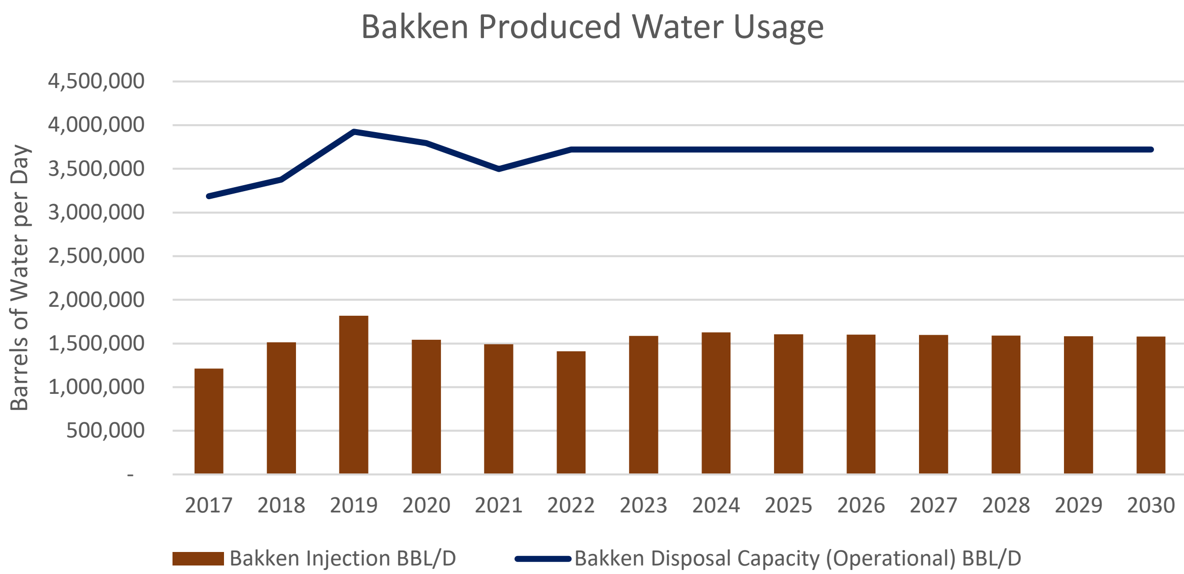

Figure 43: Bakken produced Water Usage[91]

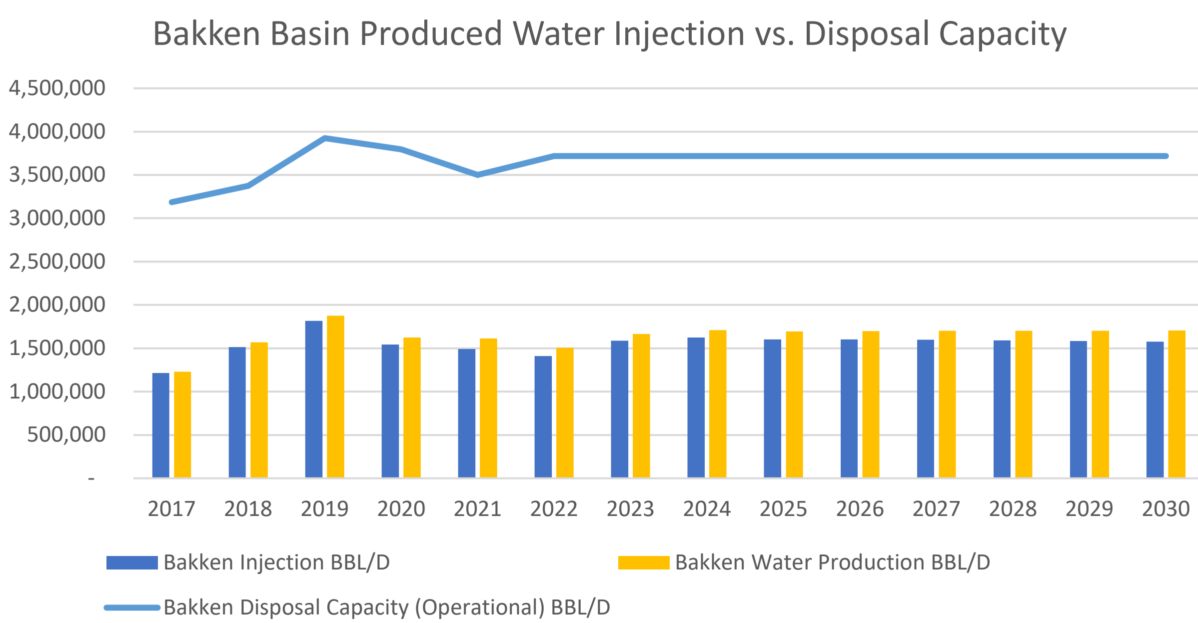

Figure 44: Bakken Basin Produced Water Injection versus Disposal Capacity[92]

[91] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

[92] ibid

The scenario of the Bakken Region meeting the daily frac demand with 100% recycled water as compared to the amount of water produced daily is shown in **Figure 45**. The stacked bar also shows the portion of water remaining to be disposed of after the recycled water amount has been subtracted from the PW total. In other words, the charts are showing the change from before and after 2022 provided the future frac demand is met through recycling and thus reducing the amount of needed injection. In this region, PW will exceed the frac demand by about four fold or roughly 1.3 M bbls/day. The increase in recycling projected to meet 100% of the frac demand will triple the current recycling amount to nearly 375,000 bbls/day reducing the injection volume by ~250,000 bbls/day moving forward, meaning that the current disposal capacity is more than enough to meet future needs, at least through 2030.

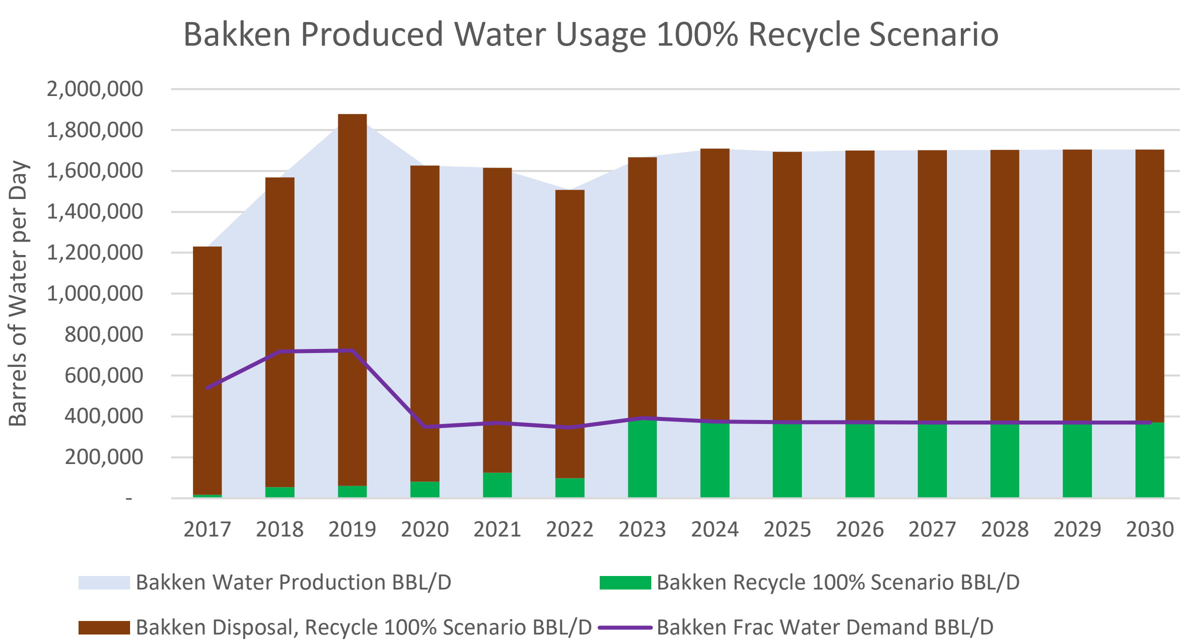

Figure 45: Bakken Produced Water Usage 100% Recycle Scenario[93]

The bar chart in **Figure 46** depicts the Bakken Region's Non-Reuse Source Water and Recycled Water volumes available for fracking, as well as the amount of water being injected in bbls/day per annum. The stacked bars show the individual percentages of each use category. As illustrated, the Non-reuse Source Water is projected to supply 75% or nearly 300,000 bbls/day of the frac demand with recycle water contributing the remaining 25% or ~100,000 bbls/day over the next 8 years from 2023 through 2030. These combined volumes (~400,000 bbls/day) only represent ~20% of the total usage, with the vast majority of usage being injection (~80%) at ~1.6 M bbls/day over this same 8-year period.

As indicated in the original GWPC PW Report, the Bakken Development Region heavily relies on a large percentage of fresh water for completion with only a small percentage of PW being recycled for ongoing completion operations. PW in the Bakken has the highest level of mean TDS of all development recycled for the next frac as the great majority of completions continue to rely on fresh water for completions.

[93] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

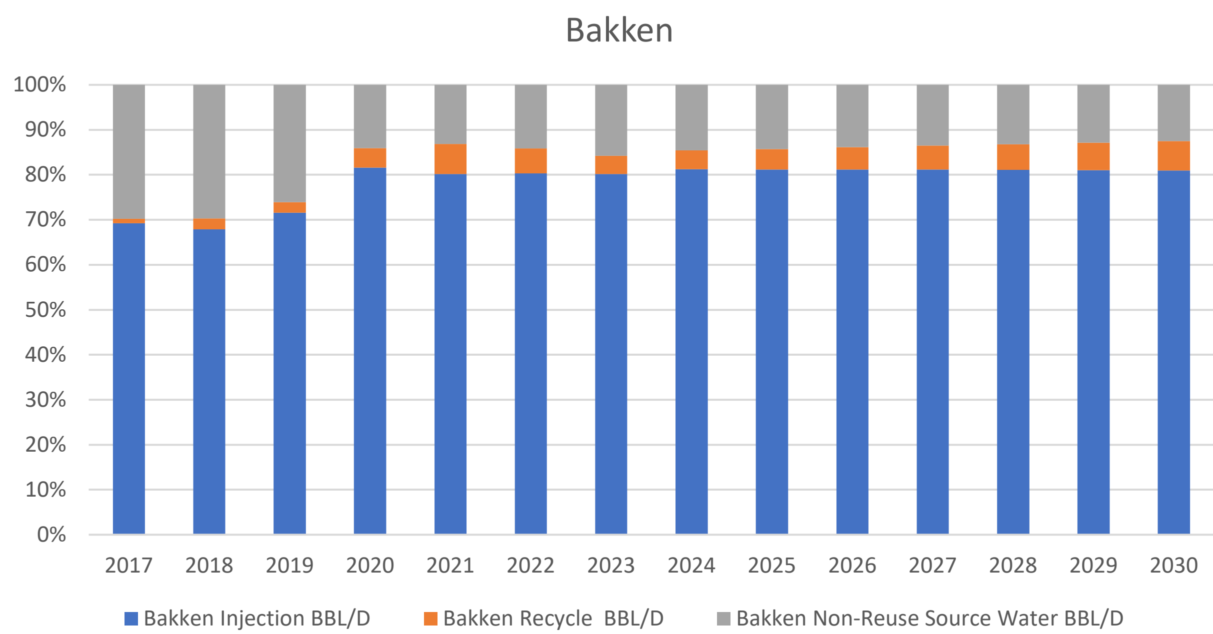

Figure 46: Available Non-Reuse Source Water and Recycled Water Volumes for Fracking[94]

3.5 Mid Continent – PW Management Operational Overview

The Mid-Continent Development Region had a significant reduction in completions over the last decade. Even with an uptick in the use of larger volumes of base water per completion, the region has seen a significant reduction in PW volumes generated.

As demonstrated in **Figures 47 and 48** the peak of oil and gas completion activities in the Mid-Continent in 2014 compelled the launch of midstream operations in this region. This effort immediately focused on fresh water sourcing and disposal, with the intent of steadily increasing PW recycling volumes. However, by 2018, well completions were less than half of the 2014 value, but the amount of base water used exceeded the amount of water used in 2014, primarily because of longer laterals being drilled. By 2020, the completion activity and associated base water volumes used in completions declined to approximately 30% of the 2018 levels. This significant reduction in completion activity has correspondingly decreased the volume of PW, thereby lessening the urgency to recycle water. To help overcome the many obstacles associated with recycling water and as mentioned earlier in this update, the Oil and Gas Produced Water and Waste Recycling and Reuse Act was signed into law in May of 2020, but appears to have had little effect on PW operations in the region. Based on a sampling of conversations with the largest midstream companies operating in the area, there has been a marginal uptick in requests for PW reuse. Currently, it is believed that recycling in this region continues to account for less than 5% of the water used in current completions.

[94] B3 Insight and Enverus original dataset and work product, based on specific development regions as requested by ALL Consulting, October 13, 2022, MSExcel file - B3 Enverus Produced Water Data rev3.1

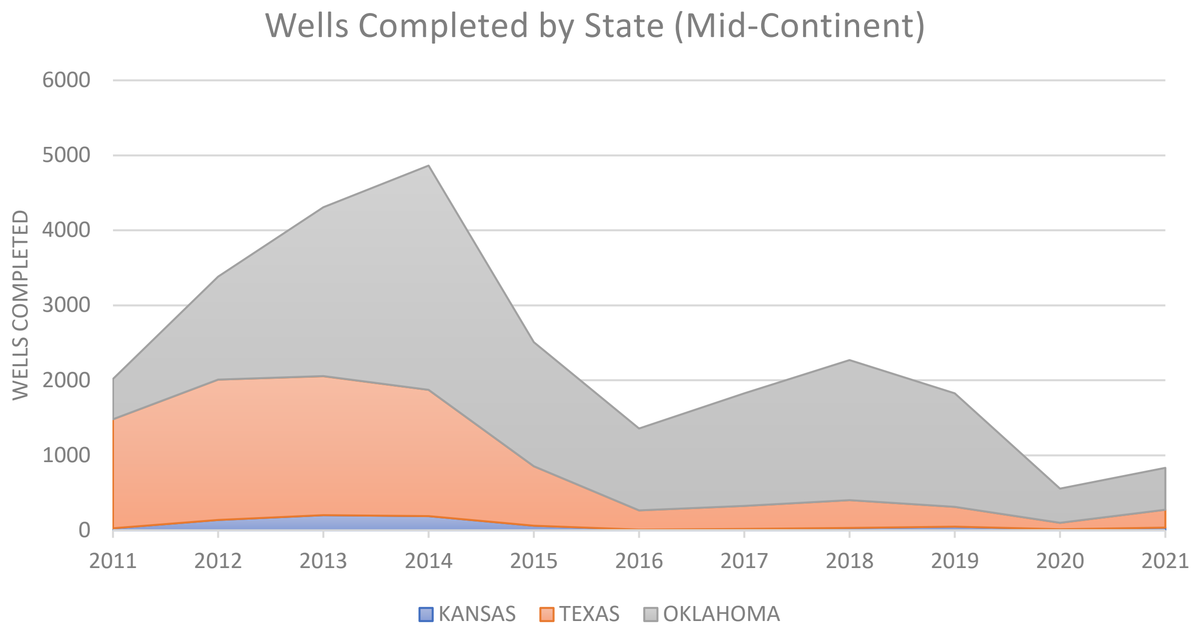

Figure 47: Wells Completed by State – Mid Continent[95]

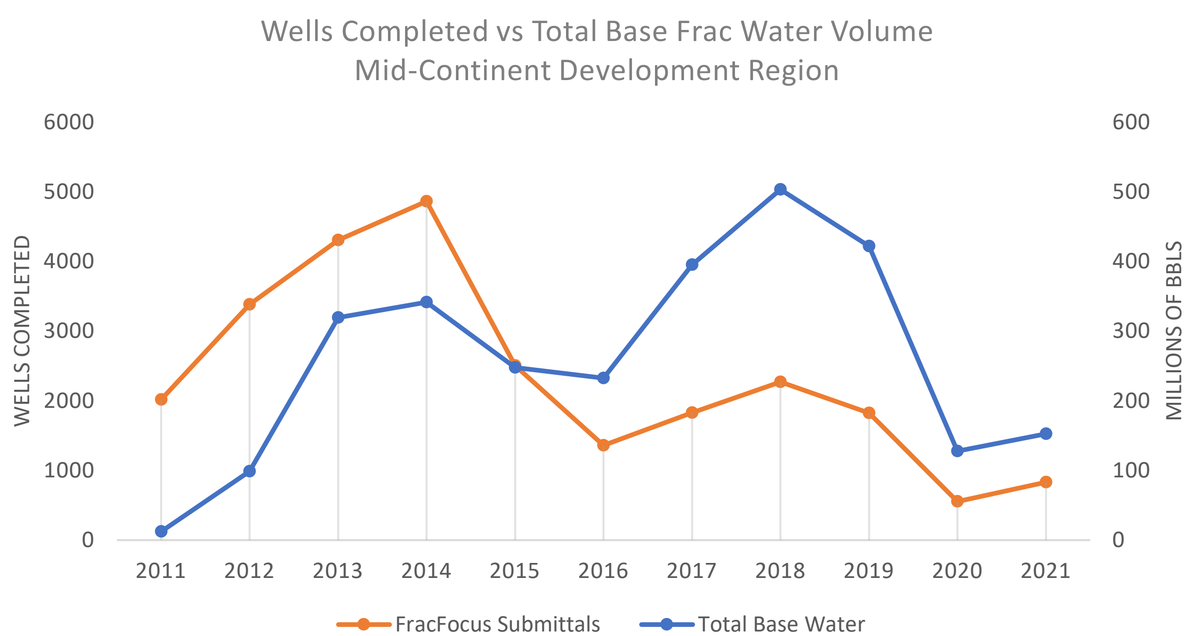

Figure 48: Wells Completed vs Total Base Frac Water Volume Mid-Continent[96]

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[95] ALL Consulting work product, Data source: FracFocus Chemical Disclosure Registry, Data Download SQL Data, analyzed accordingly, August 2022.

[96] ALL Consulting work product, Data source: FracFocus Chemical Disclosure Registry, Data Download SQL Data, analyzed accordingly, August 2022.

3.6 Rocky Mountain – PW Management Operational Overview

Similar to the Mid-Continent, the Rocky Mountain Development Region had a significant reduction in completions over the last decade as illustrated in **Figure 49**. Even with an uptick in the use of larger volumes of base water per completion, the region has seen a major reduction in PW volume generated.

The Rocky Mountain Development Region had a significant reduction in completions over the last decade and has seen a corresponding reduction in PW volumes as can be seen in **Figure 50**.

Even with larger amounts of base water to be used on a per-well basis, most sub-basins continue to recycle limited volumes of PW for completions. As shown by the graph in **Figure 49**, and mirroring the activity in the Mid-Continent Region, the peak of oil and gas development activities in the Rocky Mountain development region topped in 2012. By 2016, the level of completions declined to approximated 30% of the 2012 levels, with a slight uptick in activity in 2018. However, in 2018, well completions were less than half of the number in 2012, although the amount of base water used exceeded the amount of water used in 2012 at the peak of completion activity. This increase in base water volume is primarily attributed to longer laterals being drilled. By 2021, the base water volumes used in completions climbed to roughly 75% of the 2018 levels, although completions were again reported at about half that of the 2018 number. This reduction in completion activity has correspondingly lowered the volumes of PW to be managed, thereby diminishing much of the urgency to recycle water.

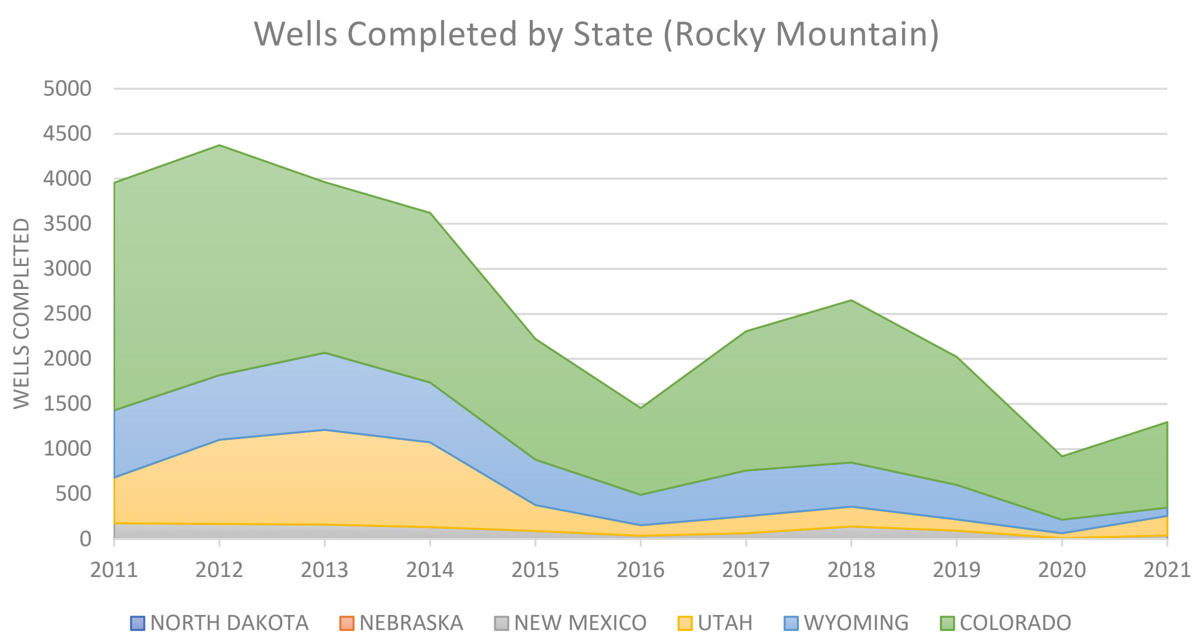

Figure 49: Wells Completed by State Rocky Mountain[97]

[97] ALL Consulting work product, Data source: FracFocus Chemical Disclosure Registry, Data Download SQL Data, analyzed accordingly, August 2022.

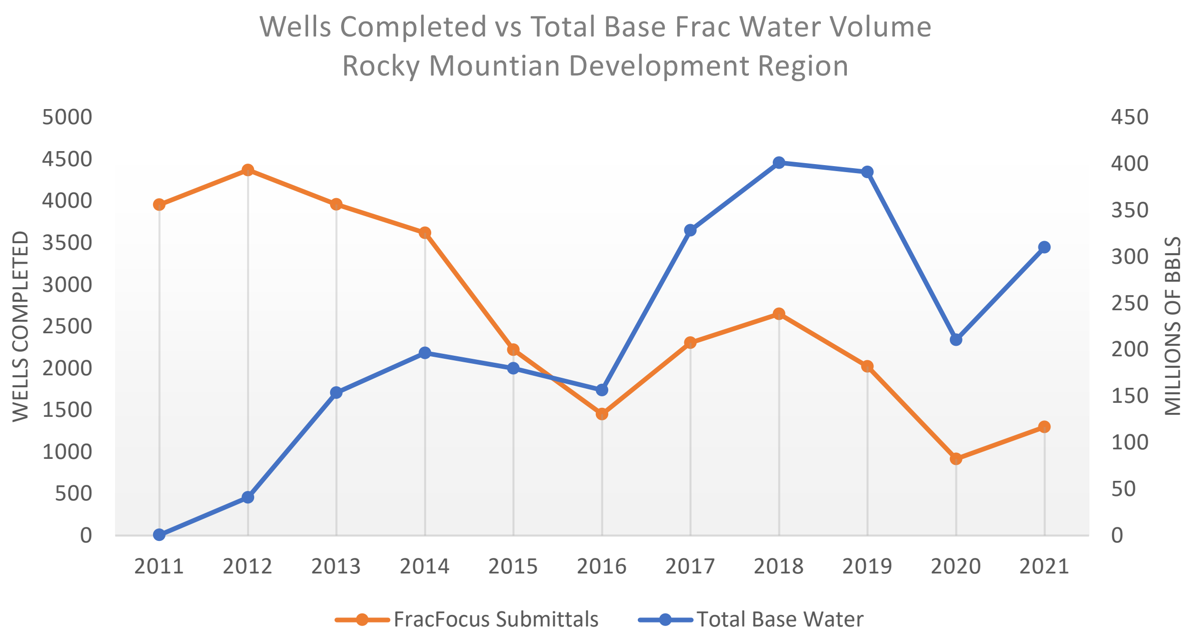

Figure 50: Wells Completed versus Total Base Frac Water Volume Rocky Mountain[98]

In the late 2000s, the focus of oil and gas development in the Rockies revolved around the Piceance and Uinta Basins. As these basins are located on the western slope of the Rockies, hydrocarbon production was accompanied by large volumes of low TDS PW. Many large PW storage and management facilities were developed and whenever plausible, recycled PW was used in completion operations. However, an abundance of water often meant that PW was stored for long periods of time in "evaporation ponds" where both natural and enhanced evaporation methods were used to reduce stored volumes.

The Denver-Julesburg (DJ) Basin and the Powder River Basins have been the most active area for oil and gas development. The DJ Basin is considered a gas basin rich in oil and liquids where the use of fresh water for completions and the disposal of PW dominates operational practices. Reuse is challenging in the basins east of the Rockies, which typically have markedly lower volumes of PW water when compared to their western slope counterparts. However, there is a growing interest in recycling to keep water transport trucks off the roads due to their proximity to urban and suburban areas. The DJ Basin is marked by very low TDS concentrations, often between 10,000 and 30,000 ppm, which gives this water the opportunity to be treated using more traditional Reverse Osmosis (RO) technologies at lower costs vs. distillation technologies. Also, due to growing interest in PW water reuse, the state of Colorado Oil and Gas Association is in the process of creating the Colorado Produced Water Consortium, which is discussed in greater detail in other sections of this report.

Alternatively, the Powder River Basin, which began with dry coalbed methane (CBM) gas development, is now considered to be a predominantly oil-rich basin, with limited natural gas production. PW associated with the Powder River Basin oil production has levels of TDS that typically range from 30,000 ppm to upwards of 70,000 ppm. Similarly, freshwater completions and PW disposal dominate the

[98] ALL Consulting work product, Data source: FracFocus Chemical Disclosure Registry, Data Download SQL Data, analyzed accordingly, August 2022.

operational situations, limiting recycling scenarios. Similarly, freshwater completions and PW disposal define typical and longstanding practices in the San Juan Basin.

3.7 Haynesville – PW Management Operational Overview

Unlike other predominantly gas-rich regions that saw an overall decline in completions due to low commodity prices, the Haynesville Development Region has seen a fairly steady level of ongoing completions activity since 2017, approaching 500 per annum, see **Figure 51**.

Even in a low-price environment, the region has sustained its completion activity primarily due to being well-positioned to supply growing liquefied natural gas (LNG) export capacity to the Gulf Coast, possibly even creating a growth opportunity. Even during periods of lower-priced natural gas, since 2017 the Haynesville has been steadily growing its production.

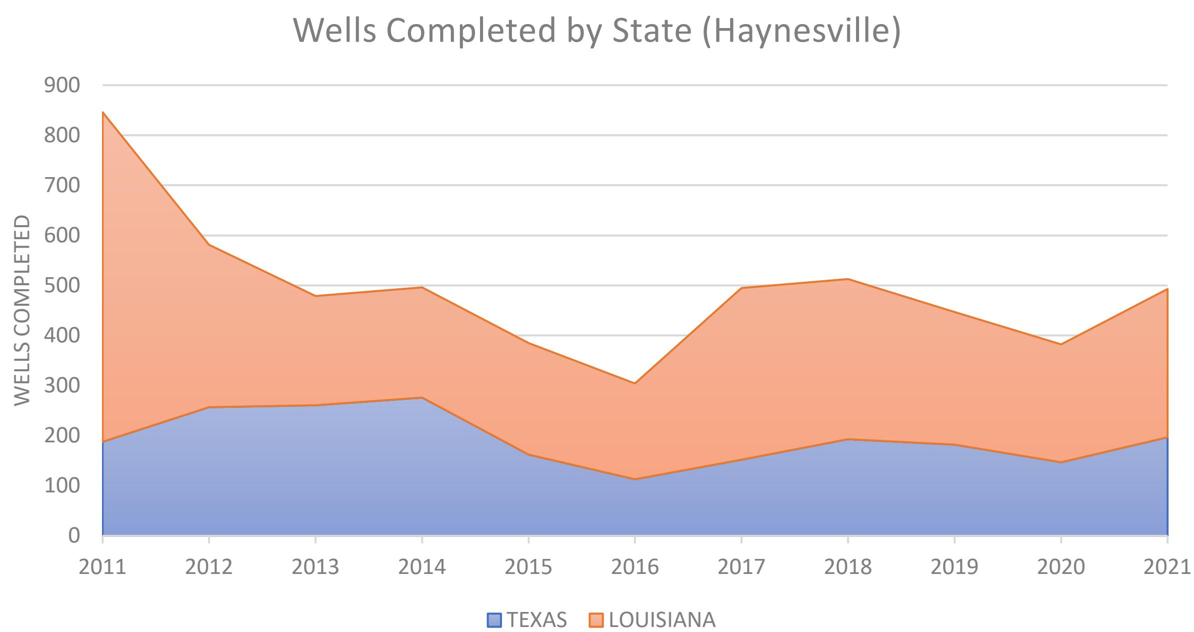

Figure 51: Wells Completed by State Haynesville[99]

With Gulf Coast LNG exports driving the region's numbers, the production decline from mid-2012 through 2016 has recovered and more than doubled since 2017 as shown in **Figure 52**. The Energy Information Administration (EIA) estimates that Haynesville production exceeded 16 billion cubic feet per day (Bcf/d) for the first time in November 2022.

As a result of the stable number of completions combined with longer lateral segments being drilled and additional water being used for completions, there has been a corresponding increase in total PW volumes.

[99] ALL Consulting work product, Data source: FracFocus Chemical Disclosure Registry, Data Download SQL Data, analyzed accordingly, August 2022.

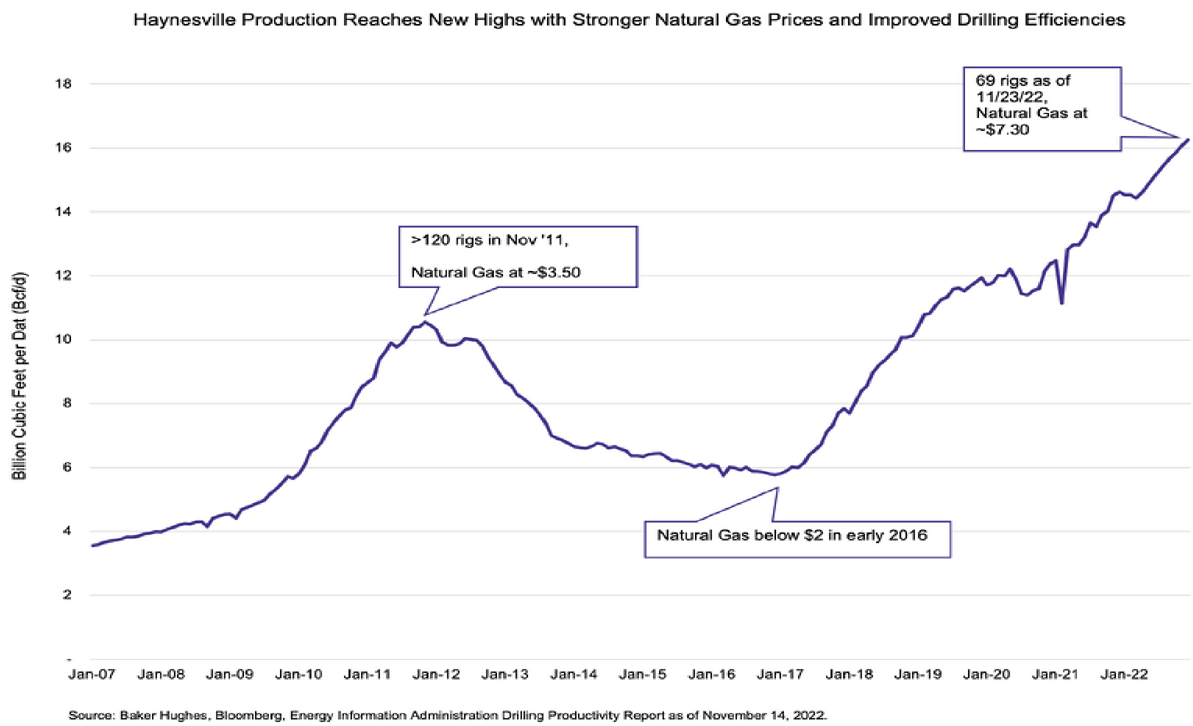

Figure 52: Haynesville Production 2007 – 2022[100]

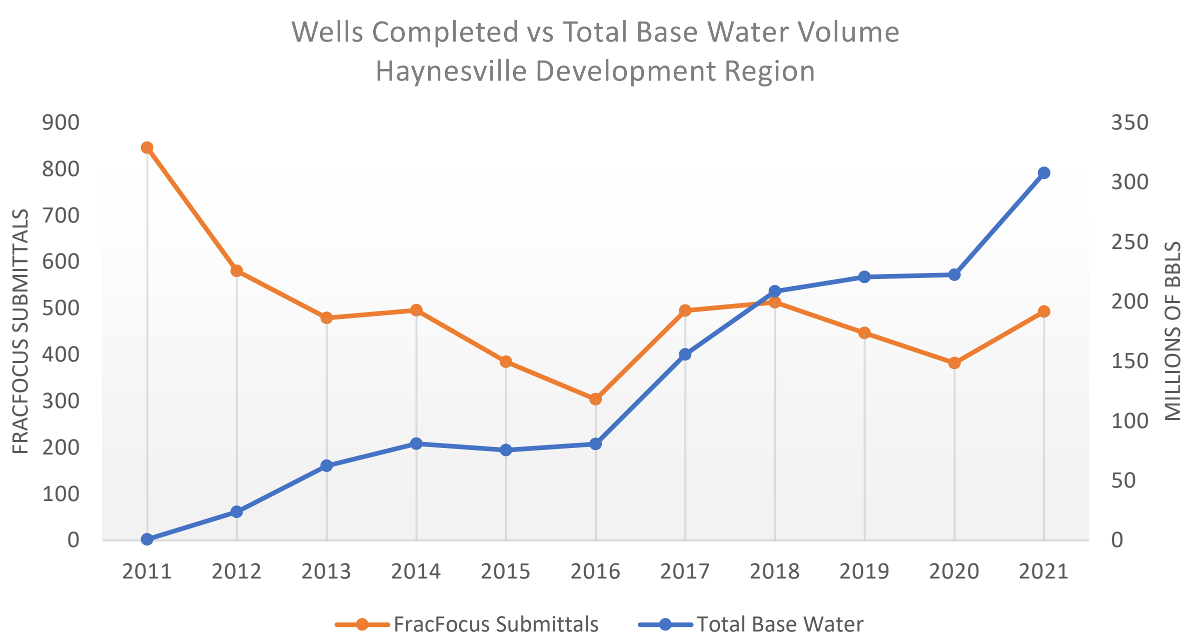

Figure 53: Wells Completed versus Total Base Water Volume Haynesville[101]

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[100] VettaFi Research, 2022. LNG Has Haynesville Humming - Benefits Midstream/MLPs, Seeking Alpha, December 07, 2022, https://seekingalpha.com/article/4562824-lng-has-haynesville-humming-benefits-midstreammlps#comments

[101] ALL Consulting work product, Data source: FracFocus Chemical Disclosure Registry, Data Download SQL Data, analyzed accordingly, August 2022.

Based on the original GWPC PW Report, Haynesville operators were recycling small amounts of PW as wells were drilled in a more scattered fashion, making the aggregation of water difficult. In addition, this formation traditionally produces low volumes of PW initially that fall off quickly. These dynamics continue to limit PW recycling opportunities with a great majority of produce water being trucked to SWDs. In addition, the Louisiana Department of Natural Resources (LADNR) has historically provided limited recycling options for operators. Typically, PW generated by any given operator was limited to go only to another one of that operator's wells, or to disposal. The LADNR appears to show a growing interest in reducing regulatory impediments to water recycling like this one in the hopes of encouraging the conservation of fresh water, but to also reduce intrastate and interstate truck traffic.

As can be seen in the graph in **Figure 53**, the peak of oil and gas development activities in the Haynesville Development Region crested in 2011, and like the other regions, total base water volumes were low per completion. Again, like the other regions, a corresponding increase in base water volumes has been experienced steadily over the past decade as longer laterials and more stable development have occurred. From 2018 through 2021, the number of completions was consistent with approximately 450/year but the base water volume continued to increase from roughly 200 Mbbls to 325 Mbbls. If this trend continues, the volumes of PW to be managed will increase, thereby resulting in a corresponding heightened urgency to recycle water.

4 Promising Produced Water Reuse Technologies and the Associated Research Needs Required for Water Reuse Outside of Oil and Gas Operations

4.1 Treated Produced Water Reuse Outlets

Once PW is treated to fresh water or discharge standards it can be reused; **Figure 54** presents the major reuse outlets for treated PW. In the figure, the only option within the energy sector includes hydraulic fracturing, while all others are outside the energy sector such as industrial, irrigation, municipal, surface water discharge, and groundwater recharge. It should be noted that any current use of a treated PW outside of the energy sector is minimal in scope and generally regional-specific and regulated by the particular State.

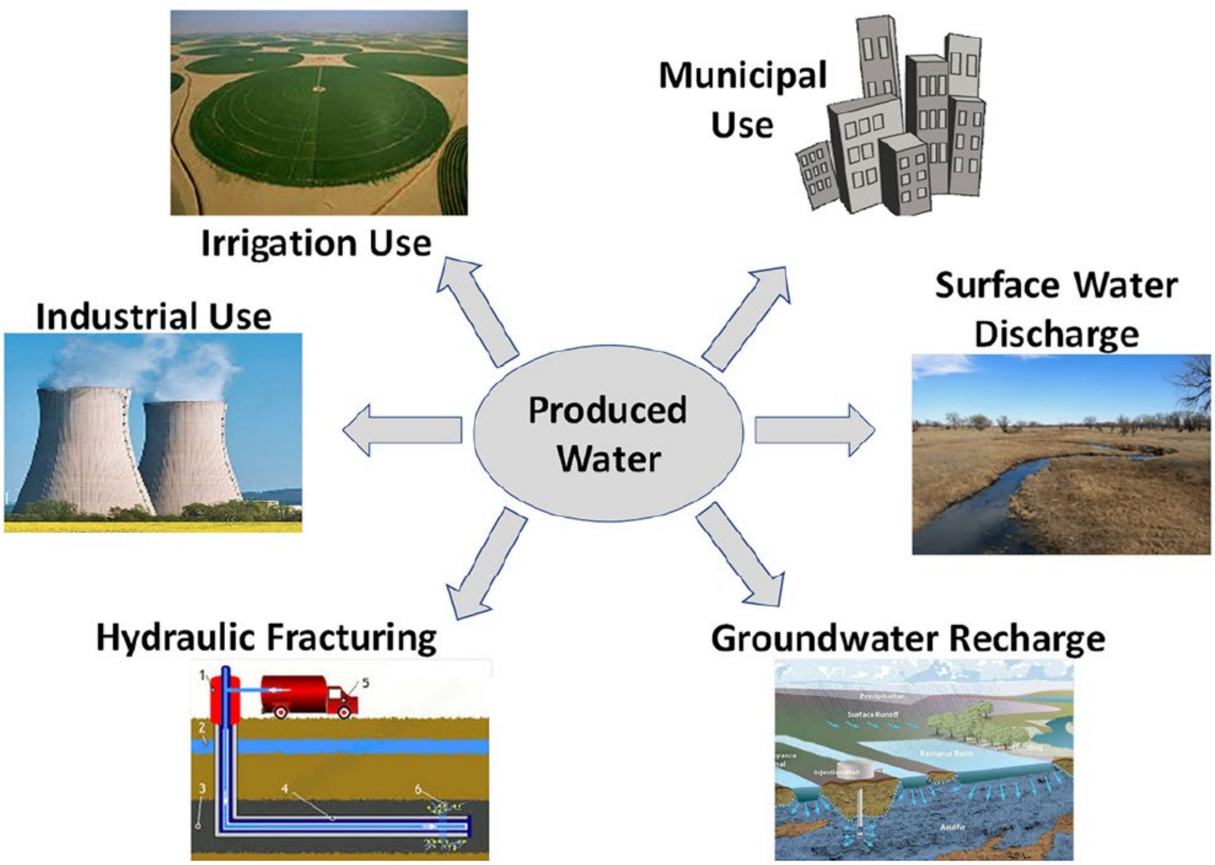


Figure 54: Major Produced Water Reuse Outlets[102]

[102] B. R. Scanlon, R. C. Reedy, P. Xu, M. Engle, J.P. Nicot, D. Yoxtheimer, Q. Yang, S. Ikonnikova, Can we beneficially reuse produced water from oil and gas extraction in the U.S.? Science of The Total Environment, Volume 717, 15 May 2020, 137085, https://www.sciencedirect.com/science/article/pii/S0048969720305957#f0010, accessed July 2022.

4.1.1 Brief Historical Overview of Treating Produced Water for Reuse

Southern California: Irrigation
For several years now, PW has been treated and reused for irrigation in Southern CA, primarily in the Bakersfield/Taft / San Ardo area. Much of that PW is generated by way of steam injection into production formations, where the heat from the steam injection reduces the viscosity of oil, which helps to enable the water and oil to come out of the formation. The PW that originated as steam, returns to the surface with a low TDS (often less than 10,000 mg/L), suitable for treatment with RO systems, creating treated water that is useful for agricultural irrigation.

Wyoming: Wamsutter Field Area – Agricultural /Livestock / Wildlife
Primarily the Wamsutter Field, which is the center of CBM developments, has historically low TDS concentrations in the PW, making it very easy to treat with RO systems, that return water for Agricultural/Livestock use.

Texas: Barnett Shale – Recycling for Completions
When fresh water was required to develop frac fluids, some operators in the Barnett Shale, led by Devon Energy, used distillation systems to treat PW to a 'fresh water' level (based on TDS) for recycling in their upcoming completion operations.

Arkansas: Fayetteville Shale – Reduced Disposal Volumes
Southwestern Energy used similar distillation systems as used in the Barnett Shale for the purposes of treating to an appropriate discharge quality. After much performance testing and approval from the state, they were able to get an NPDES permit to discharge to the White River, however, that plant was shuttered due to high operating costs.

Pennsylvania: Marcellus Shale Discharge
Eureka Resources (Service Provider) takes PW down to a commercial salt typically used for swimming pools while contaminants are removed and disposed of. After meeting approximately 40 different contaminate criteria concentrations, the recovered distillate can be discharged by way of an NPDES permit in the Susquehanna River.

Fairmont Brine Processing has a permit to discharge treated PW from its commercial plant in Marion County, WV. In addition to treating the water, the plant recovers and sells salt and calcium chloride.

Antero Resources constructed their Clearwater Facility in Pennsboro, WV (Doddridge County) with the intent of treating PW to NPDES discharge standards. This facility costs upwards of $300M, suffered numerous operational issues, and was shuddered in September 2019.

It should be noted that the 2019 GWPC Produced Water Report briefly discussed these key reuse projects.

4.2 National Efforts Supporting Beneficial Reuse

4.2.1 National Alliance for Water Innovation

The National Alliance for Water Innovation (NAWI) is a 5-year, $110M research program supported by the U.S. Department of Energy (DOE) in partnership with the California Department of Water Resources, the California State Water Resources Control Board, and multiple university, laboratory and industry partners across the nation. NAWI is headquartered at Lawrence Berkeley National Laboratory (LBNL), and forms the DOE National Desal Hub, with key locations and partnerships as shown in **Figure 55**:

Figure 55: DOE National Desal Hub Ley Locations[103]

The Hub's goal is to focus on research and development for energy-efficient and cost-competitive desalination technologies and to develop treatments for nontraditional water sources. NAWI researchers also hope to develop technologies that would enable 90% of nontraditional water sources including seawater, brackish water, and PWs to be cost-competitive with existing water sources within the next 10 years. The key research efforts and the university partners leading these efforts include:

- Conventional Produced Water – University of Texas
- Unconventional Produced Water – Colorado School of Mines
- Brackish Water – New Mexico State University
- Mining Waters – Texas A&M University

4.2.2 DOE PARETO Project

The DOE developed the Produced Water Optimization Framework in the hopes of leveraging optimization technology for PW management practices. To address these challenges, in 2021, the DOE launched a three-year, $5 million PW optimization initiative called "Project PARETO" (www.project-pareto.org). The stated goal of the initiative is to develop, demonstrate, and deploy a free and open-source PW optimization program.

[103] National Alliance for Water Innovation, Reimaging Desalination Presentation, www.nawihub.org

Given user-provided water production, demand, and transportation data, PARETO can help determine where and how to build out PW infrastructure while simultaneously improving the coordination of water deliveries over time. The framework is being designed to help organizations recognize opportunities for minimizing fresh and brackish water consumption by maximizing PW reuse in active oil and gas development areas.

The ultimate goal expected for PARETO is to become an optimization-based decision-support application that can provide users with specific and actionable recommendations on:

- Where to build water pipelines and how to size them.
- How PW deliveries should be coordinated.
- Which treatment technologies to select, where to place them, and how to size the respective plants.
- Which beneficial reuse options to consider (for example, agricultural reuse or the extraction of critical minerals).
- How to distribute treated PW and/or concentrated brine to potential end users (farmers or mining companies).

From an environmental perspective, PARETO is expected to help organizations improve the utilization of existing PW infrastructure including pipelines and storage facilities, facilitate increased piping of PW instead of trucking, as well as reduce the injection of PW into the subsurface. These improvements will also help decrease fresh water consumption by oil and gas development activities, identify beneficial reuse options within and outside the oil and gas industry, and highlight opportunities to extract critical minerals, such as lithium, from PW.

PARETO (Beta Version) is Python-based and is publicly available via GitHub.

4.2.3 U.S. Department of Energy – Produced Water Request for Information

On August 2, 2022, the DOE, Office of Fossil Energy and Carbon Management (FECM); issued a Request for Information (RFI #: DE-FOA-0002795) entitled, "Water Research and Development for Produced Water and Legacy Wastewaters Associated with Thermal Power Plants." As it relates solely to PW, the RFI was a broad appeal to all current and potential stakeholders to obtain information on concepts, processes, configurations, and systems related to advancing the treatment of PW "to minimize the need for deep-well disposal and increase the potential beneficial reuse of the water in non-oilfield applications, as currently less than one percent is reused outside oil and natural gas operations."

In addition to seeking information on specific advanced treatment technologies, this RFI sought information regarding holistic "total water treatment" solutions in addition to advances in the characterization of PW and wastewater streams associated with oil and natural gas operations. The RFI recognized the challenge associated with the high concentration of salt and other contaminants found in PW that create challenges for characterization and treatment. An additional appeal for new methods that can turn a portion of this water into a valuable product for end-use applications outside of the oilfield such as agriculture, chemical manufacturing, stream water augmentation, and aquifer recharge. Additionally, the RFI appealed to stakeholders to identify opportunities to extract critical minerals from PWs, including significant concentrations of elements such as strontium, europium, cerium, and most importantly, lithium.

Depending on the responses generated, this RFI has been touted by many in the industry as the program that could generate one of the largest investments made in DOE's history.

4.3 State Efforts Supporting Beneficial Reuse

4.3.1 Beneficial Reuse Efforts Amplified – Permian

As the Permian Development Region is a significant oil and gas development basin in the U.S. with the corresponding contribution of large PW volumes, this region is the primary focus for beneficial water reuse research and implementation. Efforts to move away from fresh water use and to convert the water produced alongside crude and natural gas into a beneficial water source continue to push forward throughout the Permian Basin. Texas legislators created the Texas Produced Water Consortium (TxPWC) to investigate and design pilot programs to find ways to treat and reuse PW. Additionally, various producers and water midstream companies are teaming up on similar research. Equally, New Mexico has formed the New Mexico Produced Water Research Consortium (NMPWRC) to do the same. Large water midstream companies are also independently evaluating promising technologies on their own, or in concert with large operators, to develop and pilot technologies and processes to treat PW with the goal of developing cost-effective and scalable treatment methods for reuse.

4.4 Current Challenges with Treated Produced Water Discharge Authorization

The preferred outcome for PW disposition is to treat for beneficial reuse or discharge. However, the challenges to obtaining discharge authorization are many, especially for those sites located west of the 98th meridian. Below is a list of notable challenges that need to be overcome before discharge authorization can be a reality:

Discharge of Unconventional PW to Waters of the U.S.

- U.S. EPA currently prohibits the discharge of unconventional PW to WOTUS
    - Treat unconventional PW to a point where it is no longer considered a waste (by that strict criterion and standard), the "de-wasted" water can now be considered for an NPDES discharge permit for release to WOTUS (i.e., a creek, stream, river, etc.)
    - The only way to date that unconventional PWs have been discharged to WOTUS (i.e., Eureka Resources, LLC in the Marcellus Basin) was by having the treatment facility meet and exceed all of the state's criteria to have the PW declassified as a waste. By meeting these strict requirements, the unconventional PW was no longer considered a waste. Once the water treatment facility was able to officially change the waste classification, that water became eligible for an NPDES permit.
    - Any water that is to be directly discharged into a body of water considered to be WOTUS would have to deal with this challenge.

Surface Discharge Standards

- States do not have discharge standards for treated PW to be released to the surface (i.e., Agricultural Use)
    - The O&G industry is working closely through the Consortiums listed above to supply sufficient numbers and types of treated water samples for comprehensive analysis by

the states and the U.S. EPA to determine what constituents need to be removed to ensure the safety of the environment and public.

Uncertainty of Constituents in PW

- **Constituents Known & Measurable, Known & Unmeasurable, and Unknown & Unmeasurable**
  - Known and Measurable – constituents are in a PW such as salts and metals and there are proven analytical techniques for high salinity matrix.
  - Known and Unmeasurable – constituents may be in PW such as NORM and many organics. These constituents may have proven techniques in a freshwater matrix, however, there are no proven analytical techniques that exist for these in a high salinity matrix.
  - Unknown and Unmeasurable (Undetectable) - constituents that are suspected to be in a given PW like "transformative by-products" from the reaction of completion fluids with existing formation brine and the geological formation itself, that have no analytical method currently available to detect or measure. Advances in analytical instrumentation are needed to detect and measure contaminants that are suspected to exist in a given freshwater matrix when discharged.

Figure 56 shows the different characteristics of PW within key formations in the Permian Development Region.

	Permian Basin	Wolfcamp Formation	Delaware Formation	Artesia Formation	Yeso Formation	Bone Spring Formation	San Andres Formation
TDS (mg/L)	10,048-384,963/ 118,253	12,136-249,459/ 95,096	12,708-360,545/ 185,433	10,050-384,963/ 94,584	10,818-381,108/ 123,784	10,048-255,451/ 105,569	10,026-391,007/ 118,879
pH	0.5-11.7/6.8	4.5-8.6/7.0	4.8-8.9/6.9	4.6-9.7/7.1	0.5-8.8/6.7	6.3-7.1/6.8	0.6-11.7/6.9
Mg (mg/L)	3-27,910/ 1,901	84-5,965/ 1,103	3-10,800/ 2,509	12-18,400/ 1,593	12-18,980/ 2,281	54.4-3396.6/ 760	2.7-27,910/ 2,087
Ca (mg/L)	24-60,073/ 6,051	211-40,800/ 6,358	24-46,346/ 12,992	87-25,315/ 3,205	235-40,420/ 6,996	174.5-21,720/ 3347	107-60,073/ 6,952
Cl (mg/L)	40-245,700/ 71,224	3,951-151,900/ 56,362	2,460-225,612/ 113,116	3,794-222,596/ 56,580	2,350-237,245/ 74,606	4,076-156,699/ 60,184	40-245,700/ 70,738
Na (mg/L)	209-143,086/ 71,224	2,625-54,068/ 29,045	5,253-109,024/ 51,113	209-128,175/ 37,470	1,529-107,396/ 35,948	1,982-80,469/ 30,723	1,123-143,086/ 35,479
K (mg/L)	14-33,962/ 861	97-742/ 362	79-1,454/ 548	65-4,620/ 505	14-1,570/ 472	109.8-1,232/ 365	8-33,962/ 1,622
Sulfate (mg/L)	18-12,320/ 2,131	84-12,080/ 1,753	84-6,280/ 1,523	18-11,900/ 2,294	35-11,800/ 2,211	111-5,250/ 1,420	22.4-12,320/ 2,362
Br (mg/L)	10-1,064/ 430	10 - 756/ 390	NA	NA	240-963/ 481	152-1,065/ 382	17-517/ 153
HCO3 (mg/L)	5-7,440/ 731	5-4,204/ 619	5-5,558/ 376	9-7,440/ 878	5-3,851/ 645	5-891/ 390	7-3,960/ 663
TOC (mg/L)	53-184/123	86-184/138	NA	NA	NA	119	NA

Figure 56: Different PW Characteristics by Permian Formation[104]

A thorough understanding of PW quality and its underlying constituent concentrations is the first step necessary to recognize how best to manage and treat PW and its associated risks and feasibility for beneficial reuse. In addition to the challenges above, other challenges for beneficial reuse include:

[104] Pei Xu, and M. Hightower, 2022, Characterization of produced water and surrounding surface water in the Permian Basin, the United States, Produced Water Society Seminar, New Mexico Produced Water Research Consortium (NMPWRC) - originally published research paper, Journal of Hazardous Materials, Volume 430, May 15, 2022, New Mexico State University, Las Cruces, NM

- The lack of an environmental and human health risk assessment framework regarding beneficial reuse.
- Primacy challenges (i.e., NMOCD vs. NMED and TX RRC vs. TCEQ vs U.S. EPA requirements).
- PW ownership.
- Treated PW ownership.
- Ownership of waste by-products generated during treatment.
- Ownership, custody, and liability transfer of waste by-products generated during treatment i.e., RCRA (where generator retains liability) and the Clean Water Act (liability transfers with custody).
- Current roadblocks to PW discharge permitting processes.
- Regulatory permitting processes that may be conducive to beneficial water reuse success.
- Quantification of current discharge treatment standards.
- Propose recommendations to regulatory agencies for consideration.
- Limitation of technical resources for state agencies to evaluate and establish standards for water characterization and treatment.
- Policy/ regulatory protections in place for liability relief.
- Bonding and policy safeguards.
- Impacts of waste recharacterization from Non-Hazardous Oilfield Waste (NOW) to RCRA waste and how this designation could impact reuse implementation and cost.
- Impacts of RCRA if imposed vs the NOW exemption, and how this designation would impact:
  - Waste generated by treatment process(es).
  - The management of air emissions from tanks/impoundments and other treatment processes.
  - The classification and management of radioactive wastes.
- Associated precursors that may impede progress to the challenges listed above:
  - Primacy challenges,
  - Characterization of PW,
  - Constituents can be widely variable,
  - Difficult matrix for analysis for low detection levels,
  - Lacking or limited analytical methods,
  - Constituents of PW.
- Analyzing the current PW and solid waste stream practices in states affected.
- Potential impacts associated with RCRA exemption from treating PW for beneficial reuse (discharge).

4.5 Permian Produced Water Consortiums Developed to Drive Needed Regulatory, Operational, and Research

4.5.1 Texas Produced Water Consortium

The Texas Produced Water Consortium (TxPWC) was created by Texas Senate Bill 601 in 2021 and was tasked with two primary responsibilities; 1) to develop a white paper for the Texas Legislature discussing the feasibility of water recovery from PW (Completed August 2022), and 2) to develop at least one economically feasible pilot project for state participation in a PW facility based on promising technologies (2023/2024).

Several Committees were formed to support this effort, which includes:

- Steering
- Technologies
- Policy
- Standards/Specification
- Hazards/Risks
- Water Quality
- Transportation / Infrastructure
- Economics

TxPWC, in conjunction with various industry, academic, and stakeholder groups are working toward:[105]

- Suggested changes to laws, changes specifically designed to find and define beneficial use outside of the oil and gas industry.
- Suggested guidance for establishing fluid oil and gas waste permitting and testing standards.
- Economically feasible pilot project for state participation in a facility designed and operated to recycle fluid and oil and gas waste.
- An economic model for using fluid oil and gas waste in a way that is financially viable and efficient and protects public health and the environment.
- Energy off-sets continue to be explored in order to make existing technology economically viable in the current PW market.
- R&D centered around new technologies is being undertaken by various water-focused companies to identify more energy-efficient beneficial re-use treatment methods.
- Combining RRC land application permits, in conjunction with semi-salt tolerant crop irrigation, appears to be the most logical first step for beneficial re-use implementation.
- Subsequent beneficial re-use methods that will require additional R&D and permitting scope include aquifer storage and recovery (ASR), salt-tolerant concrete manufacturing, and discharge to State Waters.

4.5.2 New Mexico Produced Water Research Consortium

The New Mexico Produced Water Research Consortium (NMPWRC) was formed in the fall of 2019 as a joint agreement with NM State University and the NM Environmental Department (NMED), they began earnest operations and advocacy in 2020. In 2021, the consortium issued a Request for Proposal (RFP) for pilot systems to be technically reviewed that same year. Numerous pilots were completed in 2022 and information from these pilots can be found at https://nmpwrc.nmsu.edu.

Various Supporting Committees have been formed under the NMPWRC, including:

- Government Accountability Board
- Technical Steering Committee
- Risk and Toxicology
- Infrastructure and Scenarios
- Public Education and Outreach
- Treatment Technology
- Produced Water Data and Portal

[105] Texas Tech University, Texas Produced Water Consortium: https://www.depts.ttu.edu/research/tx-water-consortium/

NMPWRC has focused on the challenges associated with PW characterization, recognizing the complexity of this water chemistry, and the constituents of concern in PW (formation water and flowback water) including:

- Suspended solids, oils, and grease
- Salts (referred to as dissolved solids)
- Dissolved organics (e.g., petroleum hydrocarbons, volatile and semi-volatile compounds)
- Metals
- Dissolved gases (e.g., H_2S, NH3)
- Naturally Occurring Radioactive Material (NORM)
- Microorganisms
- Chemical additives (well completion and ongoing well maintenance)
- Transformation / degradation products
- Unknowns

High salinity and complex water chemistry cause challenges in analytical methods. PW quality is highly variable by region and within any given region by formation, formation depth, and time in production. As a result, there appears to be a need for more consistent PW quality data, especially when it comes to the type and concentration of primarily inorganic ions.

The NMPWRC published a Gap Analysis and Resource plan (January 2022) outlining emerging science and technology gaps that needed to be filled to ensure reuse outside of the oilfield in January 2022.[106] The gaps identified include:

- the collection and development of more detailed PW quality data and the use of more robust water quality analysis systems;
- the support for research on emerging innovative PW treatment approaches and collection of more operational PW treatment technology cost and performance data to facilitate technology implementation;
- the establishment of more appropriate and detailed risk and toxicity methods for assessing treated PW toxicity and risk to human and environmental health and safety for various fit-for-purpose PW reuse applications;
- the quantification of cost/benefit/risk issues and tradeoffs associated with fit-for-purpose - treatment and reuse of PW; and
- the issuance of information in a form that will allow New Mexico environment and natural resource management agencies to establish science-based policies and regulations to oversee the discharge, handling, transport, storage, and recycling or treatment of PW and co-products safely and effectively for various reuse applications.

At a high level, the efforts identified in this Gap Analysis and Research Plan address the following issues of the use of treated PW for fit-for-purpose use: 1) the technical, cost, and engineering risks, 2) the public and environmental health and safety risks, 3) support for reducing freshwater use and improving freshwater supply sustainability under emerging climate conditions, and 4) timely dissemination of

[106] M. Hightower, P. XU, J. Sullivan Graham and D. Dixon, 2022. A Gap Analysis and Research Plan for the Reuse of Produced Water Addressing the Technical, Economic, and Health and Safety Risks of Fit-for-Purpose Reuse, New Mexico Produced Water Research Consortium, New Mexico State University, January 2022.

research results to inform and educate the public, industry, and government agencies on the viability of the treatment and reuse of PW for fit-for-purpose uses outside the oil and gas industry.

The proposed research effort is broad and will require significant funding to accomplish. Under current funding of less than $1 million per year, the efforts noted above will not be fully completed until 2025. With further funding reductions, these efforts will take significantly longer. With increases in funding and support from legislators, sponsors, collaborators, and agencies to $3 million per year, the program can be significantly accelerated and completed by the end of 2024.[107]

Another challenge in NM regarding the future of beneficial reuse revolves around water ownership with transfer and waiver of liability challenges. When compared to Texas, the transfer of water ownership in NM faces challenges where regulatory boards show reluctance to transfer liabilities associated when transfer produced to other owners/industries. This makes all ownership stakeholders reluctant to transfer water ownership and the associated liability to a third party.

4.5.3 Notable New Consortium Addition: Colorado Produced Water Consortium

The Colorado Oil and Gas Conservation Commission (COGCC) has initiated the development of the Colorado Produced Water Consortium (CPWC). This consortium is in its early stages of development with four key committees identified:

- Advisory
- Recycling of Produced Water Infield
- Legal / Policy Guidance
- Beneficial Use Outside of Oil and Gas

4.6 The Key to Beneficial Reuse of Produced Water - Overcoming the Following Challenges Associated with Desalination

When it comes to the beneficial reuse of PW in any of the major development basins, the primary challenge to overcome is the desalination of the water by way of treatment and managing the associated products and wastes that are generated. Aside from the regulatory and liability challenges associated with the discharge of PW discussed above, this simple answer does provide a comprehensive perspective of the technical and economic challenges associated with large-scale PW desalination systems.

What many view as perhaps a more arduous challenge arises regarding the disposition of the salt removed from the water. This subject is often overlooked by industry due to the general awareness that very large desalination plants exist across the globe without serious concern about the salt recovered from the water. What makes this a greater challenge for PW vs. shoreline desalination processes will be discussed later in this section. To offset this challenge, there are technologies and many more in development that allow for the removal of water vapor from a PW without reducing the PW to salt.

[107] M. Hightower, P. XU, J. Sullivan Graham and D. Dixon, 2022. A Gap Analysis and Research Plan for the Reuse of Produced Water Addressing the Technical, Economic, and Health and Safety Risks of Fit-for-Purpose Reuse, New Mexico Produced Water Research Consortium, New Mexico State University, January 2022.

4.6.1 Desalination of Produced Water

4.6.1.1 Beneficial Reuse Requirements and Options:

There are countless options for the beneficial reuse of treated PW which include irrigation, agricultural, municipal, industrial, livestock, groundwater recharge, etc. All options require water to meet a low salinity standard. The primary challenge faced by the beneficial reuse of PW is the removal of Total Dissolved Solids (TDS) or dissolved salt from the PW matrix. The table in **Figure 57** represents the salinity values of different types of water and their prospective uses. For unrestricted beneficial reuse or discharge options, the table indicates that salinity must be <0.05% salinity (<500 ppm TDS).

Salinity Status	Salinity (%)	Salinity (ppt)	Use
Fresh	< 0.05	< 0.5	Drinking and all irrigation
Marginal	0.05 – 0.1	0.5 – 1	Most irrigation, adverse effects on ecosystems become apparent
Brackish	0.1 – 0.2	1 – 2	Irrigation certain crops only; useful for most stock
Saline	0.2 – 1.0	2 – 10	Useful for most livestock
Highly Saline	1.0 – 3.5	10 – 35	Very saline groundwater, limited use for certain livestock
Brine	> 3.5	> 35	Seawater; some mining and industrial uses exist

Figure 57: Different Types of Water Salinity Values [108]

4.6.1.2 Representative TDS Levels of Produced Water by Development Basin

The TDS Concentrations of PW from the USGS Produced Waters database (version 2.3), which includes supplemental data for the New Mexico region of the Permian Basin provided by the New Mexico Institute of Mining and Technology (NMIMT) Petroleum Research and Recovery Center (PRRC), and data from the USGS in the Eagle Ford Play is presented in **Figure 58**. The labeled values represent the median PW TDS concentrations, within each play area, of wells classified as either shale gas, tight oil, or CBM, except for the Permian value, which includes wells that are classified as conventional hydrocarbon wells completed in unconventional formations (i.e., Wolfcamp, Bone Spring, Cline, Spraberry, and Dean).

[108] Laqua Horiba, 2016. Measuring Salinity of Water, Table 1: Water Salinity Source: Understanding Salinity, Department of Water, Government of Western Australia, https://www.horiba.com/ind/water-quality/applications/water-wastewater/measuring-salinity-of-water/ Retrieved October 2022.

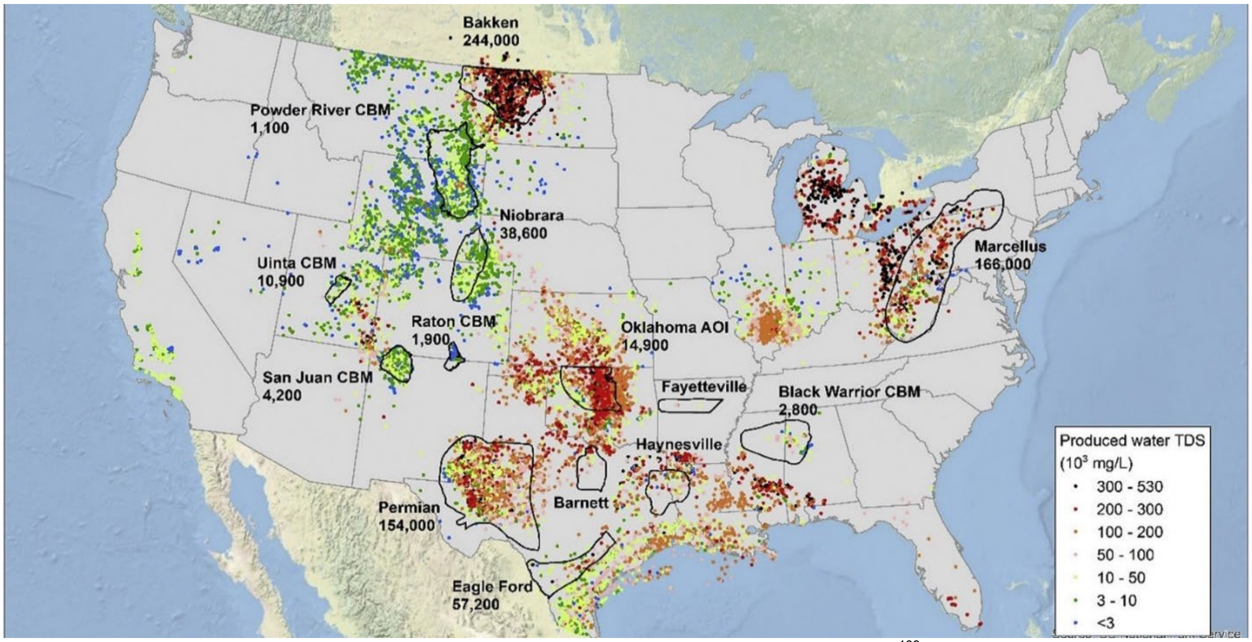


Figure 58: USGS TDS Concentrations of PW[109]

From this graphic, it is apparent that the four largest oil and gas development areas in the U.S., (Permian, Eagle Ford, Marcellus, and Bakken) have a median range of TDS from a minimum of 57,000 ppm to a high 244,000 ppm. In addition to the graphic above, additional sources indicate that the average TDS of the Haynesville Development Region is ~80,000 ppm.[110]

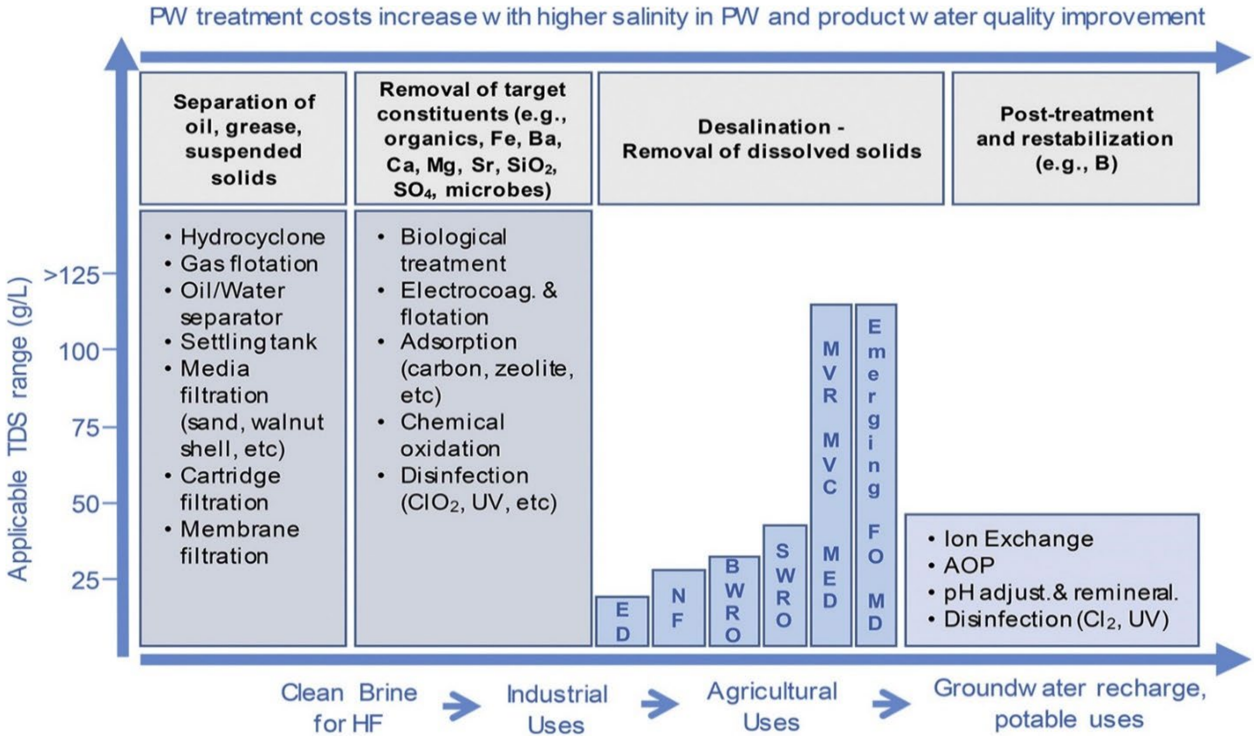
4.6.1.3 Desalination Technology Offerings and Limitations

As indicated in the original GWPC Produced Water Report, in most situations, PW requires significant pretreatment prior to being subjected to any desalination process. However, as pretreatment technologies and their efficiencies were discussed in the original GWPC report, the focus of this report will continue to be on the desalination processes that currently show the highest promise in the most prominent development areas.

The most viable currently available treatment technologies for PW are presented in **Figure 59.** These include minimal treatment of PW for hydraulic fracturing (clean brine), desalination for beneficial reuse in various sectors, surface water discharge, and groundwater recharge, as well as the post-treatment technologies required.

[109] B.R. Scanlon et al. 2020. Can we beneficially reuse produced water from oil and gas extraction in the U.S.?, Science of the Total Environment, Volume 717, May 15, 2020 (137085), Data Source: the USGS Produced Waters database (version 2.3) with supplemental data provided by the New Mexico Institute of Mining and Technology (NMIMT) Petroleum Research and Recovery Center (PRRC), https://www.sciencedirect.com/science/article/pii/S0048969720305957

[110] Henderson, Claire, Acharya, Harish, Matis, Hope, Kommepalli, Hareesh, Moore, Brian, & Wang, Hua, 2011. Cost Effective Recovery of Low-TDS Frac Flowback Water for Re-use. United States. https://doi.org/10.2172/1030557



Legend: ED: electrodialysis; NF: Nanofiltration; BWRO: brackish water reverse osmosis; SWRO: seawater reverse osmosis; MED: multiple effect distillation; MVC: mechanical vapor compression; MVR: mechanical vapor recompression, emerging technologies including FO: Forward Osmosis; MD: membrane distillation. AOP: advanced oxidation processes

Figure 59: Currently Available PW Treatment Technologies[111]

The most prominent and proven water desalination technology deployed across the world is RO which becomes increasingly inefficient when TDS concentrations exceed 35,000 ppm which is reflective of the salinity concentration in seawater. As the overwhelming amount of PW in the U.S. is well above the levels to be treated by RO, including the Permian (median TDS concentration – 154,000 ppm), this technology is not applicable.

A total of ten desalination technologies were discussed extensively in the original 2019 GWPC PW Report, and they are as follows:

- Nano-Filtration (NF)
- Forward Osmosis (FO)
- Reverse Osmosis (RO)
- Electrodialysis
- Thermal Distillation (Vapor Distillation – VD)
- Membrane Distillation (MD)
- Evaporator/Crystallizer
- Multiple Effect Distillation (MED)
- Adsorption
- Ion Exchange

[111] B.R. Scanlon et al. 2020. Can we beneficially reuse produced water from oil and gas extraction in the U.S.?, Science of the Total Environment, Volume 717, May 15, 2020 (137085), https://www.sciencedirect.com/science/article/pii/S0048969720305957 .

When it comes to treating high salinity PW, only Thermal (Vapor) Distillation would be considered "mature and proven" for this application. These distillation technologies typically consist of a Mechanical Vapor Compression/Recompression (MVC/MVR) component and have been in use for more than a decade in the oilfield treating PW with limited acceptance due to throughput and costs. As discussed in the original report, thermal distillation technologies often require extensive pretreatment of the water before processing including the removal of hydrocarbons, TSS, and all hardness cations.

Since the issuance of the GWPC PW Report in 2019, there has been little noteworthy progress made with regard to the treatment of high salinity PW using any of the technologies listed above. For this reason, these technologies will not be addressed further in this update. However, there have been a few new notable technologies that have appeared on the scene in addition to the original 10 listed. Two of the technologies that show promise in treating high salinity are introduced in the following subsections for future consideration.

4.6.1.3.1 Low-Temperature Distillation

The claimed advantages of Low-Temperature Distillation (LTDis®) include:[112]

- No pretreatment of PW for TSS or hardness as required by Vacuum Distillation or MVC.
- Limitation to the amount of hydrocarbon that can be in the water.
- Distilled under a vacuum, meaning lower energy demand as well as contributing to a reduction in the hard scale formation within the units, allowing for longer runs without degradation of the thermal transfer at the surface.
- Creates a large number of small droplets,
  - Larger surface area due to evaporating and condensing of droplets,
  - No phase change on solid surfaces,
  - Minimum scaling risk (evaporation done in air, not on surfaces).
- Plant scalable from 3,000 to 30,000 bwpd distillate per modular train.
- Made from standard metals (exotic materials not required).
- Tolerant of fluctuating and intermittent heat sources,
  - Operates at a temperature as low as 167 deg. F (75 deg C).

4.6.1.3.2 Graphene Membranes

Graphene-based membranes have special nanochannels and can offer beneficial properties for PW desalination. While impressive endeavors have been undertaken to enhance membrane performance and widen their application, there is still limited literature on the development and future directions of graphene-based membranes for the desalination of PW. In this regard, graphene nanomaterials, with their unique physicochemical properties are novel and unproven yet appear to be promising at the lab level but have not yet been demonstrated commercially. These materials can offer extraordinarily high surface area, mechanical durability, atomic thickness, nanosized pores, and reactivity toward polar and non-polar water pollutants. These characteristics impart high selectivity and water permeability, and

[112] EnergyNow.com, Distill Industrial Wastewater Using Waste Heat with Innovative Low-Temperature Distillation (LTDisTM) Technology, EnergyNow Media, June 9, 2021 https://energynow.com/2021/06/distill-industrial-wastewater-using-waste-heat-with-innovative-low-temperature-distillation-ltdistm-technology/

thus theoretically could be designed for specific water streams to remove all contaminants, including TDS.[113]

4.6.2 Desalination and Disposal Challenges for High TDS Produced Water

4.6.2.1 Fresh Water Recovery / Disposal Volume Reduction Ratios

Based on a cross-section of midstream and SWD operations, a concentrated brine of ~260,000 ppm TDS (at ambient temperatures and pressures) would be the acceptable maximum target limit for ongoing disposal in SWD wells without fear of creating additional and unwanted solids precipitation downhole. Using vapor distillation methods, a reasonable expectation of required incoming PW volumes (at TDS levels ranging from 100,000 – 200,000 ppm) to generate 10,000 bbls of distillate (fresh) water at < 500 ppm TDS is presented in **Figure 60**.

Incoming Water TDS (ppm)	Incoming Volume (bbl)	Heavy Brine Volume (bbl) at 260,000 ppm	Distillate Volume Recovered (bbl) at <500 ppm	Percent Distillate (Fresh) Water Recovered
100,000	16,250	6,250	10,000	61.54%
110,000	17,333	7,333	10,000	57.69%
120,000	18,571	8,571	10,000	53.85%
130,000	20,000	10,000	10,000	50.00%
140,000	21,667	11,667	10,000	46.15%
150,000	23,636	13,636	10,000	42.31%
160,000	26,000	16,000	10,000	38.46%
170,000	28,889	18,889	10,000	34.62%
180,000	32,500	22,500	10,000	30.77%
190,000	37,143	27,143	10,000	26.92%
200,000	43,333	33,333	10,000	23.08%

Note: Heavy brine is concentrated to 260,000 ppm TDS, and distillate is <500 ppm TDS.

Figure 60: Expected Water Recovery and Waste Brine Volumes from High Salinity PW[114]

4.6.2.2 Disposition of Salt Recovered from Desalination

The largest and most successful desalination plants process seawater and are located in the Middle East. Currently, the largest seawater desalination plant in the world is the Al-Jubail Desalination Plant in Saudi Arabia which desalinates a whopping 1.4 Million cubic meters (8.81 Mbbls) of seawater per day![115] The United Nations backed a global study in 2019 to determine the amount of concentrated brine vs. the amount of desalinated water generated and determined that the ratio is 1.5:1 (concentrated brine to desalinated water). Using this ratio, the Al-Jubail plant per day generates approximately 5.3 Mbbls of concentrated brine and 3.5 Mbbls of desalinated water. The concentrated brine presents a large

[113] Homaeigohar, S., Elbahri, M. Graphene membranes for water desalination. NPG Asia Mater 9, e427 (2017). https://doi.org/10.1038/am.2017.135 August. 25, 2017

[114] Crystal Clearwater Resources, Fit for Purpose Calculation for GWPC Produced Water Report – 2023 Update, March 22, 2023, Apoorva Sharma, COO via email.

[115] The Economic Times, Inside the world's biggest water desalination plants in Saudi Arabia, Oct. 13, 2020. https://economictimes.indiatimes.com/news/international/saudi-arabia/inside-the-worlds-biggest-water-desalination-plants-in-saudi-arabia/articleshow/78639741.cms retrieved October 2022.

disposal challenge. While this is not an issue in Saudi Arabia, it is an almost unconquerable issue in the PW plays.

There are countless differences between seawater desalination when compared to the desalination of PW, but this discussion will focus on the two primary differences. First, the TDS concentrations of seawater globally average approximately 35,000 ppm. These lower concentrations of TDS allow for the use of RO, which is the most economical and scalable desalination technology available. Secondly, every seawater desalination plant is located along a coastline which ensures direct access to a single inlet seawater source. Once seawater is processed through the RO system, the concentrated brine (disposal stream) is then pumped back into the sea through a system of diffusers. This allows the inlet source for the seawater and the outlet for the disposal of the concentrated brine to be the same. This tried-and-true process dynamic is exceedingly viable for water-starved countries, like those in the middle east, and is viable for even the most water-starved areas of the world.

Alternatively, PW in the Permian Basin typically exceeds 150,000 ppm TDS which is four times more saline than seawater. In addition, PW originates below the surface, and the nearest and most feasible disposal alternative is to inject this concentrated brine into the subsurface by way of SWD wells.

The next most often asked questions are, “What if we further reduce the concentrated brine solution all the way to dry salt? Is there a market to sell the salt?”

4.6.2.2.1 Brine Concentrator and Crystallizer

The waste stream of all desalination systems largely comprises of concentrated brine liquid. Removing the water from concentrated brine and leaving behind only a dry mixture is very energy intensive.

Efforts to treat high salinity PW have enjoyed some measures of success in the Marcellus with Eureka Resources, Fairmont Brine Processing, and Antero Resources (which were highlighted at the beginning of this section – “Summary History of Treating Produced Water for Reuse.” Largely due to the elevated cost of treatment and transport, commercial processes like Eureka and Fairmont are treating relatively low volumes (upwards of 10,000 bbls of PW per day). What makes the Marcellus unique is that it largely lacks the conductive geology required for successful underground injection, which severely limits access to SWD wells.

4.6.2.3 Treatment Economics

As shown in **Figure 61**, costs can vary widely depending on the volume of water to be treated and the contract duration. Market intelligence places the cost for Vapor Distillation somewhere between RO and crystallization. The cost is largely driven by economies of scale (Volume x Contract Duration).

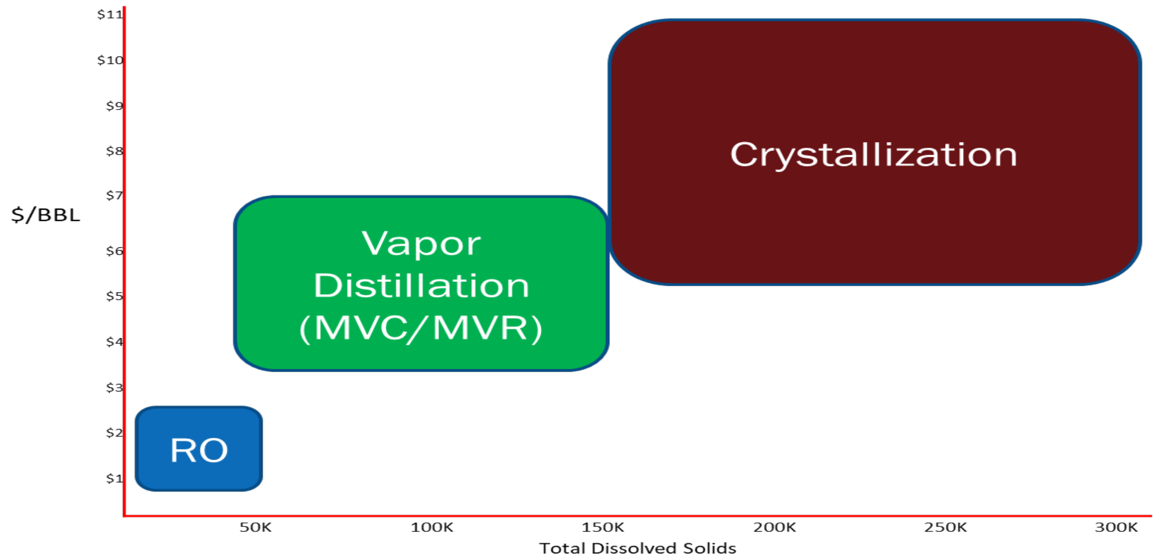


Figure 61: Economic Costs per Barrel of Water Treated as a Function of TDS[116]

Figure 61 presents the economic costs per barrel of water (42 gallons) treated as a function of (TDS) in water by treatment technology including RO, vacuum distillation/mechanical vapor recompression (VD/MVR), and crystallization.

To treat PW with higher concentrations of TDS (as in the Marcellus), VD processes and MVC must be used and they typically operate in a range between $3.50 to $7.00 per barrel. The waste product from this process is then further treated with crystallization technologies, at a cost that typically falls in the range of $6 - $11 per barrel. Cumulatively, the cost range for both treatments would be $9.50 to $18.00 per bbl. This relatively high cost per barrel treatment is often significantly more than other disposition options available to the majority of operators in the region.[117]

As mentioned earlier, these processes require significant energy resources. It has been estimated that VD/MVC + Crystallization process requires 6-8 kWH (kilowatt Hours) of electricity for every barrel of PW processed. Assuming a plant to be constructed would process 50,000 bbls/day, this would use approximately 109.5 to 146.0 GWh per year (Gigawatt hours per year). In 2014, the EIA estimated the average household electric consumption by a household of 2.59 people to be approximately 11 megawatt hours (10,932 kWH) per year. This means that a 50,000 bbls/day VC/MVC + Crystallization Plant would have the equivalent energy demand of a city with a population of 25,000 – 34,000 people.

4.6.3 Waste / Product Generation from Desalination

Desktop Case Study Example – Demonstrating the Challenge of Beneficial Reuse*

The table in **Figure 62** shows capacities for treating PW that range between 5,000 and 300,000 bbls/day, as well as bbls/day of products and waste such as filter cake, distillate, salt, and CaCl2 brine.

[116] National Academies of Sciences, Engineering, and Medicine (2017). Flowback and Produced Waters: Opportunities and Challenges for Innovation: Proceedings of a Workshop. Washington, DC: The National Academies Press., Rick McCurdy, Chesapeake Energy, page 34.

[117] National Academies of Sciences, Engineering, and Medicine (2017). Flowback and Produced Waters: Opportunities and Challenges for Innovation: Proceedings of a Workshop. Washington, DC: The National Academies Press., Rick McCurdy, Chesapeake Energy, Slide 4.

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

NOTE: bbl = billion barrels; MGD = million gallons per day.

Figure 62: Product and Waste Generation[118]

Looking at a comparative VD/MVC/Crystallization thermal treatment process that treats 50,000 bbl/day of PW at a single plant (as highlighted in red above), assumptions are as follows:

- TDS concentration - 200,000 mg/L
- Divalent (scaling) cation concentrations - 20,000 mg/L
- Prior to the thermal treatment process, PW will require significant pretreatment to effectively remove/reduce:[119]
    - Hydrocarbons
    - Divalent (scaling/hardness) cations
    - TSS

At this 50,000 bbl/day throughput, the product and waste generation will be as follows:[120]

- Waste: 533 tons of divalent cation solid waste to be landfilled
    - Calculated volume assumes removal as filter cake,
    - Most roll-off boxes used in industry today will hold ~20-30 tons of solids,
    - Out of this plant – Approximately 1 truck every hour, 24 hours per day for disposal
        - This will account for substantial transportation costs and add truck traffic to the road.
- Once cations are removed, water then goes to VD/MVC/Crystallization, where the product and waste generation is as follows:
    - Product - 40,000 bbls of fresh water or distillate per day
    - Product /Waste ~1,000 tons per day of salt will be generated (after the 40,000 bbl of distillate is boiled off).
        - Salt as a Product - If salt were to be sold commercially, this would likely be shipped by rail car, approximately 8 rail cars full of Sodium Chloride (NaCl) every day,

[118] National Academies of Sciences, Engineering, and Medicine (2017). Flowback and Produced Waters: Opportunities and Challenges for Innovation: Proceedings of a Workshop. Washington, DC: The National Academies Press., Rick McCurdy, Chesapeake Energy, page 34.

[119] National Academies of Sciences, Engineering, and Medicine (2017). Flowback and Produced Waters: Opportunities and Challenges for Innovation: Proceedings of a Workshop. Washington, DC: The National Academies Press., Rick McCurdy, Chesapeake Energy, pages 33-34

[120] Select Energy Services, "Sustainability Outlook: Exploring the Potential of Produced Water in 2023" – Nov. 9, 2022, Presentation, Rick McCurdy, VP Sustainability and Innovation https://selectenergyses.wistia.com/medias/7vzwkk47xm

        - Salt as a Waste - If sent to a landfill, an additional 2 trucks per hour to the highways.
- Calcium Chloride ($CaCl_2$) is another salt that is in the PW matrix and cannot be discharged. In this scenario, an additional 10,000 bbls/day of $CaCl_2$ brine would need to be disposed of or sold.
    - Note - $CaCl_2$ has a much higher saturation level than NaCl so tremendous heat and energy are needed to convert to salt.
    - However, there is a commercial demand for $CaCl_2$, outside of the oil and gas business, so depending on situational economics, recovery of $CaCl_2$ may be justified.
        - Additionally, $CaCl_2$ brine is a high-density fluid that can be used during drilling or workover operations for well control.

Salt (NaCl) – A Marketable Commodity?

People often ask, "Isn't there a demand for salt to sell it? If so, wouldn't this help offset the cost of treatment?" Yes, there is, but NaCl is primarily in demand as a deicing medium in the Northern U.S. due to cold weather plus population density. However, salt is currently bountiful throughout the world. So much so, it costs as little as $35.00 per ton delivered in Utah.[121]

4.6.4 High Salinity Produced Water Desalination: Secondary Treatment and Market Challenges

4.6.4.1 Ammonia /Methanol / Remineralization

In addition to the challenges listed earlier, products like ammonia and methanol and/or their precursors tend to pass through thermal distillations processes and collect in the distillate, requiring an additional post-treatment step. Any additional technology at the discharge of any thermal process must be very effective at removing ammonia as some NPDES discharges require it to be as low as 1 ppm ammonia in effluent. For ammonia in the distillate, an oxidative catalyst can be deployed that would destroy the ammonia in the desalinated effluent. Other alternatives include ion exchange and biological-type treatments. A possible treatment method for methanol includes Granular Activated Charcoal (GAC) would strip out the methanol.

As the water produced from thermal technologies is essentially demineralized (distilled) water that lacks a minimum level of hardness. As a result, this water is often termed as being aggressive in its preferential affinity to absorb hardness minerals from its environment. As a result, most of these demineralized/distilled waters must go through a remineralization step prior to being discharged which increases treatment cost and footprint.

4.6.4.2 NORM / TENORM

Both solid and fluid wastes associated with oil and gas development in Pennsylvania can contain NORM and technologically enhanced naturally occurring radioactive material (TENORM). These wastes are the result of naturally occurring low-level radioactive material found in most soils and rock. When the concentration of NORM is increased through physical processing or reuse of wastewater, the radioactive material is then referred to as TENORM.

[121] Ninja Deicer, Bulk Rock Salt Price per Ton: Guide for 2022-2023 Season, https://ninjadeicer.com/blogs/resources/bulk-salt-price-guide-what-you-can-expect-to-pay-in-2020 retrieved December 2022.

The PA DEP conducted a widespread study of NORM/TENORM associated with oil and gas operations in Pennsylvania in 2013.[122] PA DEP analyzed radiation levels in a range of oil and gas waste streams (e.g., flowback waters, PWs, treatment solids, drilling cuttings, etc.) along with the potential exposure to workers and the public through the transportation, storage, treatment, and disposal of these wastes. This study found that flowback waters contained Radium-226 concentrations between 551 to 25,500 picocurie per liter (pCi/L) and Radium-228 between 248 to 1,740 pCi/L. Furthermore, unfiltered PW (including both conventional and unconventional wells) contained Radium-226 concentrations between 40.5 to 26,600 pCi/L and Radium-228 concentrations between 26.0 to 1,900 pCi/L.[123]

Regarding NORM/TENORM: David J. Allard, MS, CHP, and Director, Bureau of Radiation Protection PA Dept. of Environmental Protection issued the following statement:[124]

"Given the millions of gallons of water used to hydro-fracture tight shale formations to release trapped natural gas (in PA), the high TDS associated with flow-back water, and reports of high radium content of the used frac water, PADEP undertook an expansive study." Mr. Allard goes on to say, "It was concluded there was a low potential for workers or members of the public to receive radiation exposure above the 100 millirems per year public dose limit, but there was potential for contamination of the environment from spills. Further evaluation of landfill TENORM waste disposal, road brine spreading, pigging operations, and some wastewater treatment operations was warranted."

This statement confirms and is representative of what is understood by the marketplace that PW alone rarely contains high enough levels of NORM/TENORM to create concern. However, the industry has a keen awareness that when subsurface solids are aggregated and accumulated in a single location, that is a cumulative effect in radiation levels by higher NORM/TENORM levels. Most operators manage this concern by increasing the frequency of solids removal from the treatment site.

4.6.4.3 First Large-Scale, High Salinity PW Desalination Treatment Plant

There are a very limited number of high salinity PW treatment plants that create fresh water and salt as products. As mentioned earlier, Eureka Resources and Fairmont Brine operate small facilities in the Marcellus. Additionally, and as mentioned in the original 2019 PW Report, Antero Resources contracted with Veolia Water Technologies to construct the "first of its kind," large-scale, high salinity PW treatment plant capable of treating 60,000 bbl/day of Marcellus PW. This facility, called the Antero Clearwater Facility (Doddridge County, WV), was designed to process PW and produce fresh water and salt as the primary products. The salt was intended to be sold to municipalities to use for deicing roadways initially, but ultimately Antero permitted and constructed a landfill adjacent to the plant to dispose of any excess salt.[125]

The produced water characteristics, physical and constituent concentrations, of the feed to the plant varied widely, which impacted the treatment cost and stable operation of the process. While the process demonstrated the capabilities of producing salt and water to specification, changing market

[122] Interstate Oil and Gas Compact Commission (IOGCC) - 2022 TENORM Reference Guide and Summary of State Regulations for TENORM in Oil and Gas. IOGCC https://iogcc.cmail19.com/t/r-l-tjiiuruk-bkluylyhtu-o/
[123] ibid
[124] ibid
[125] Global Water Intelligence, 2019. Antero setback fuels rumor of Veolia reorganization, https://www.globalwaterintel.com/news/2019/49/antero-setback-fuels-rumour-of-veolia-reorganisation accessed May 2023.

conditions (commodity prices, drilling activity, and reduced demand for fresh water) appeared to have an impact on the economic viability of the plant. Operation of the Clearwater Facility was suspended in the Fall of 2019.

The fate of the Clearwater Facility serves to remind us that the treatment of PW presents a complex set of technical and economic challenges that will continue to influence investment decisions in this area.[126]

4.7 Environmental, Social, Governance and Produced Water

Some of the most important Environmental, Social, and Governance (ESG) metrics to measure within PW management operations reside under the environmental aspect, which includes:

- Energy Efficiency
- Carbon Footprint
- Emissions
- Climate Change and Pollution Mitigation
- Waste Management
- Water Usage

The most common actions taken to diminish ESG impacts in PW management commonly focus on reducing emissions by installing pipelines, which in turn lowers truck traffic and lessens exhaust emissions. Another ESG impact reduction measure worthy of consideration is the active replacement of fresh water with recycled or brackish water sources in frac fluids. However, brackish water used as the primary frac-ing fluid is expected to be phased out over time as brackish water is likely the next source of available fresh water for landlocked arid regions like the Permian Development Region. Based on this expectation, many companies anticipate the ongoing use of brackish water to be used for upcoming completions as a medium-term strategy at best.

Other key supporting elements to improve ESG metrics include:[127]

- Fixed infrastructure (i.e., Pipelines/Storage)
  - Improved safety,
  - Reduced risk of spills,
  - Reduces trucking and related emissions.
- Automation
  - Improved pump efficiencies and emission control,
  - Improved safety by reducing driving to site, and proximity hazards,
  - Increased visibility and accuracy of reporting ESG key performance indicators (KPI's).
- Water Recycling
  - Advancing chemistry increases the potential for water recycling and reuse,
  - Preventing the use of excess chemicals by minimizing over-treating water,
  - Reducing disposal and potential seismicity,
  - Reducing stress on aquifers.

[126] United States Securities and Exchange Commission, Antero FORM 10Q filing, for the quarterly period ended March 31, 2020.

[127] Select Energy Services, Sustainability Outlook: Exploring the Potential of Produced Water in 2023" – Nov. 9, 2022, Presentation, Rick McCurdy, VP Sustainability and Innovation https://selectenergyses.wistia.com/medias/7vzwkk47xm

4.8 Mineral Extraction Opportunities for Produced Water

Due to the rise in PW volumes and its associated management costs, there is a growing interest in the possibility of obtaining beneficial minerals from PW to alleviate the related overall costs and management for disposal. The mineral gaining the most attention for extraction and recovery is currently lithium, because of its demand and desirable commodity price. Other substantial minerals present in PW often include cerium, europium, and strontium, however, lithium remains the best candidate for recovery in commercial volumes.

"Mining lithium requires a highly selective recovery technology, extracting just the lithium from PW," said UL's Daniel Gang, director of the Center for Environmental Engineering and Protection. "The technology is still in the benchtop-laboratory or pilot scale. The target is dilute," he said, referencing the need to separate low concentrations of lithium from high concentrations of "competing elements" by processing "absolutely huge amounts of PW" to recover lithium at commercial volumes." The recovered lithium then needs to be further refined to reach a 90-95% purity level, he added.[128]

Current extraction technologies indicate that lithium chloride (LiCl) concentrations in PW should be >100 ppm for economic viability. There is hope that advancements in technology reduces that minimum viability concentration to 50 ppm. In the largest PW generator in the U.S., samples indicate that LiCl concentration in the Permian ranges from 20-40 ppm. At these low levels, Lithium must be "up-concentrated" significantly.[129]

Figure 63 depicts the LiCl concentrations in PW and some oilfield brines. Even with rapidly advancing technological developments in the field of lithium extraction, the apparent challenges appear to be many. One of the biggest obstacles revolves around the need to separate low concentrations of lithium from other elements within the high salinity matrices often found in PW. In addition, to maximize the economic value, recovered lithium must reach purity levels > 99% for its primary application – lithium batteries.

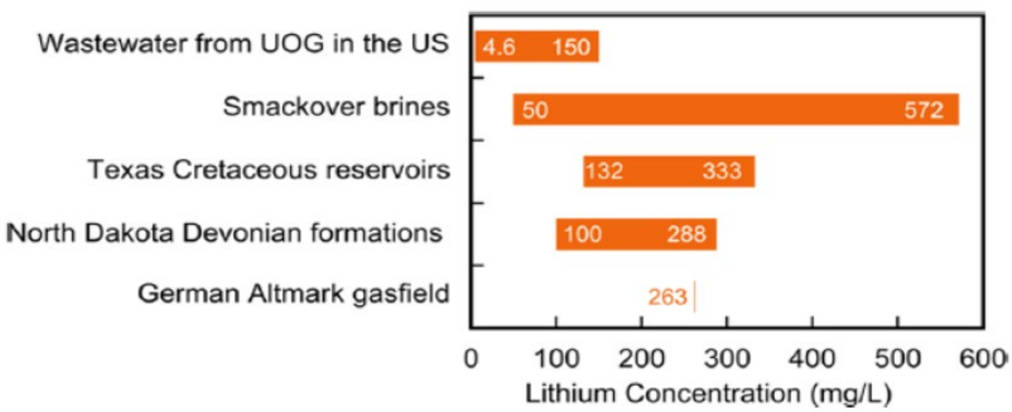


Figure 63: Lithium Chloride Concentrations in Produced Water and some Oilfield Brines[130]

[128] M. Veazey, 2022. Natural Gas, Oil Brines Could Help Supply Tight Lithium Market, Natural Gas Intelligence, June 4, 2022 https://www.naturalgasintel.com/natural-gas-oil-brines-could-help-supply-tight-lithium-market/

[129] Harnessing Vacuum Membrane Distillation for Beneficial Reuse and Lithium Extraction, Zachary Sadow, Chairman & CEO, KMX Technologies, Produced Water Society Annual Conference, Midland, TX, August 17, 2022.

[130] ibid

5 Summary of Findings

Since the 2019 GWPC Produced Water Report, the most notable changes in the PW marketplace have revolved around the expanding oil and gas development activities in the Permian Development Region. To support the large volume of PW generated in this region, there has been an equivalent growth in the water midstream services sector. The increase in high salinity PW volumes is occurring concurrently with the growing number and magnitude of seismic events, creating mounting constraints on subsurface disposal. As a result, the Permian is facing a confluence of PW management challenges at a scale unseen in any other region. These market dynamics guided the necessity for this addendum to focus on the Permian as it encompasses the most notable changes in regulatory, operational, and research activities. The Permian also leads in the advancement of efforts to improve PW management, recycling, and reuse which will likely impact other regions in the foreseeable future.

As the volume of PW generated within the oilfield appears to drive increases in induced seismicity, regulatory changes will continue to impact the subsurface injection of PW. However, as the volume of PW generated is significantly greater than the volume of water that could be used for recycling, developing viable methods to reuse PW will be an important area for the industry. As a result, significant amounts of state, federal, and private dollars are being invested to support the quest for optimal technological and operational advancements.

The beneficial reuse of PW in any of the major development basins faces a number of difficult challenges. Currently, it is difficult to characterize PW quality due to problems with analytical measurements, interference caused by the high salinity matrix, and a lack of suitable analytical standards. In addition, current regulations for water reuse outside of the oilfield related to discharge requirements were not developed to address PW issues. Lastly, one of the greatest challenges to overcome is the desalination of high salinity PW and managing the associated products and wastes subsequently generated. Aside from the regulatory and liability challenges associated with the use of waters outside of the oilfield, a focus on water treatment alone does not provide a comprehensive operational and economic perspective of the technical challenges with large-scale PW desalination systems.

The crux for the beneficial reuse of PW outside of the oilfield revolves around the desalination of large volumes of high salinity PW. Even though there is increasing investment and optimism surrounding new and emerging desalination technologies, high salinity PW requires thermal distillation approaches to treatment for reuse. Even as desalination technologies advance and become increasingly more efficient and economical, challenges remain around the practical levels of fresh water recovery that can be attained while generating a concentrated brine waste stream that can be injected into SWD wells on a consistent basis. For greater levels of fresh water recovery from the desalination process, one must proceed beyond concentrated brine and progress towards crystallization options, which become increasingly impractical due to the disposition of massive quantities of salt and other solid by-products. As treatment and disposition technologies associated with high salinity PW continue to emerge, much more research is required to safely reuse PW in other sectors or discharge to surface waters. As a result, the most immediate and impactful way of managing PW focuses on maximizing in-field recycling efforts.